Optical & electrical control of topological defects in confined chiral liquid crystals

July 19, Ljubljana, Slovenia

Ivan I. Smalyukh

Department of Physics,
Liquid Crystals Materials Research Center,
Renewable & Sustainable Energy Institute
University of Colorado at Boulder

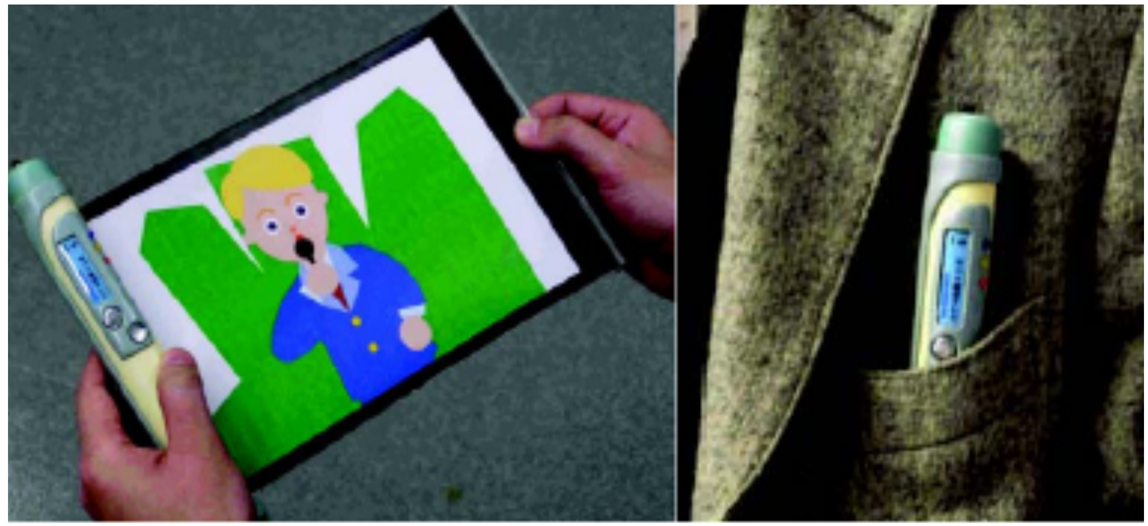
Electrically-Controlled LC director

→Collective response to external fields;

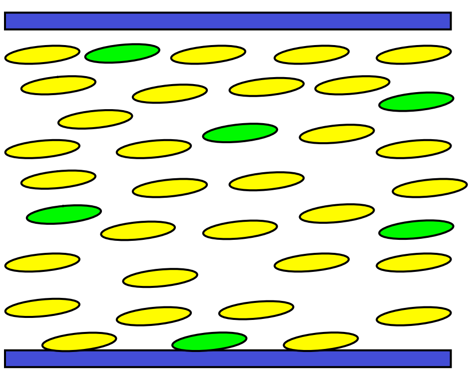
→Electric-field-induced realignment in LCs;

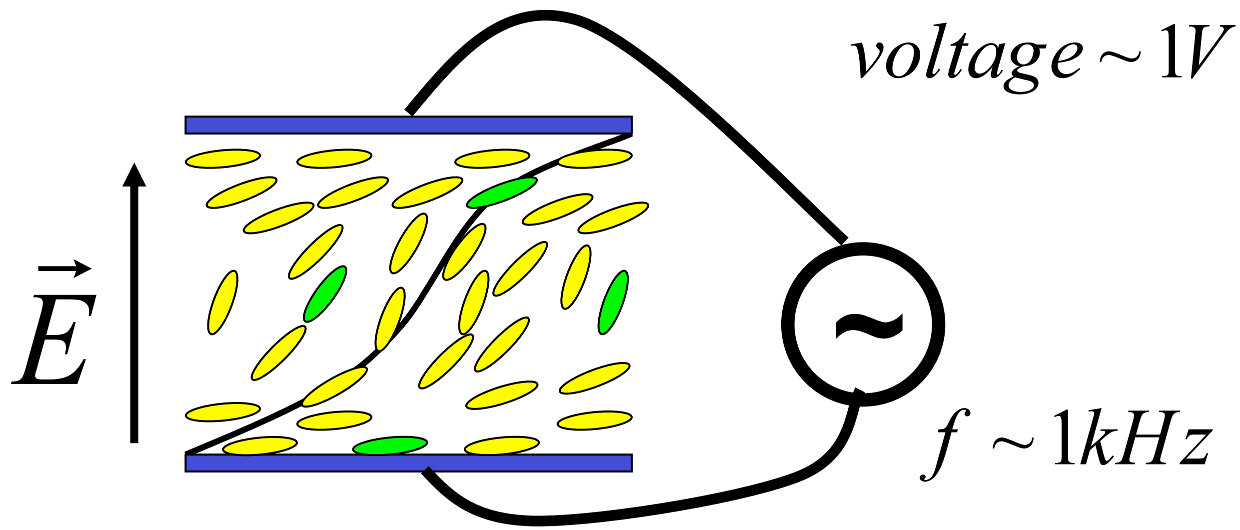
→Minimize the electric-field term of free energy:

$$F_e = -\frac{\varepsilon_0}{2}\int_V \Delta\varepsilon(\vec{E}\cdot\hat{n})^2\, dV$$



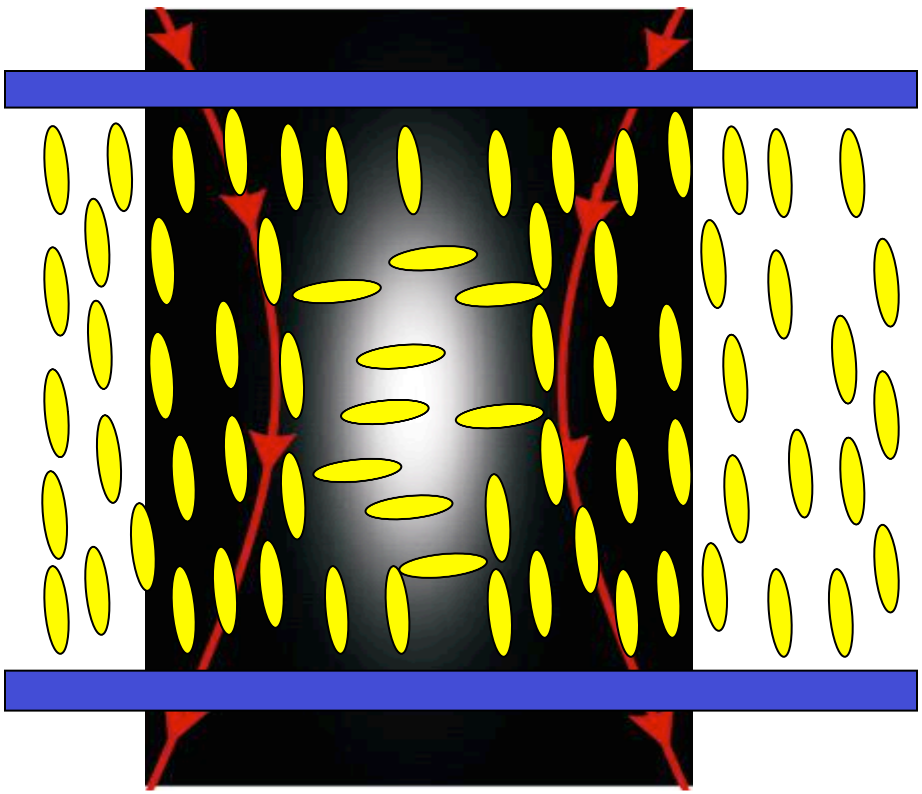
→Displays and electro-optic devices



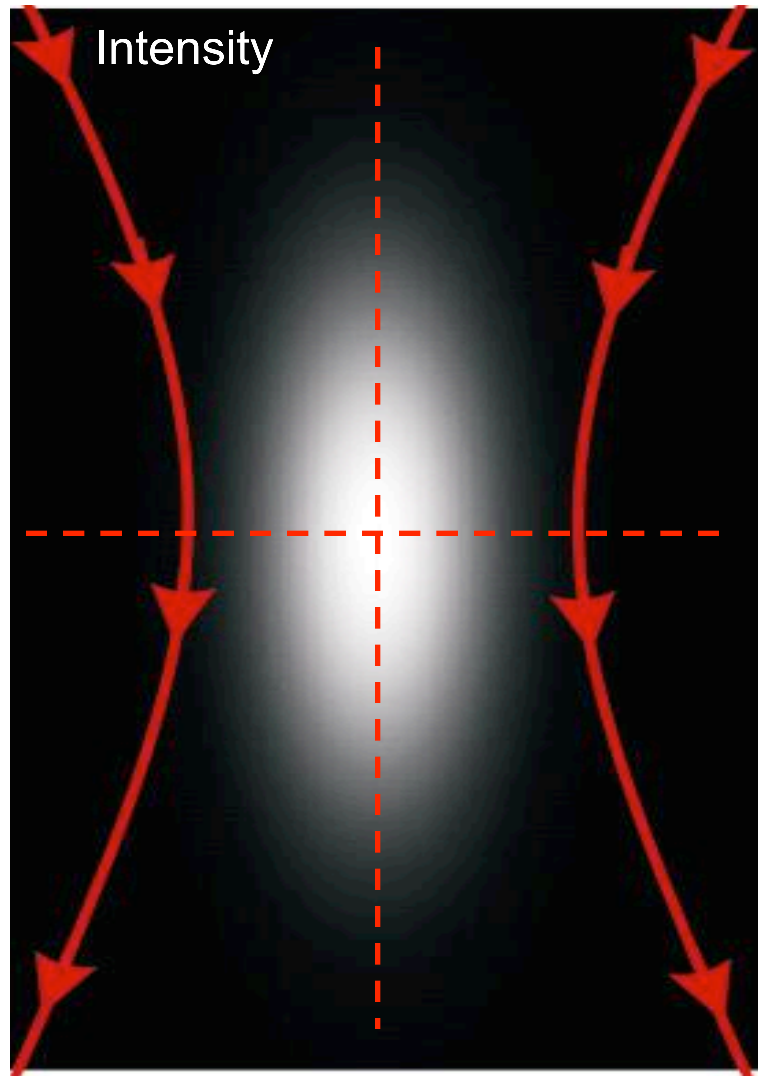


Optically-induced molecular realignment

Optical realignment



Focused Gaussian beam



→Realignment by electric field of laser beam;

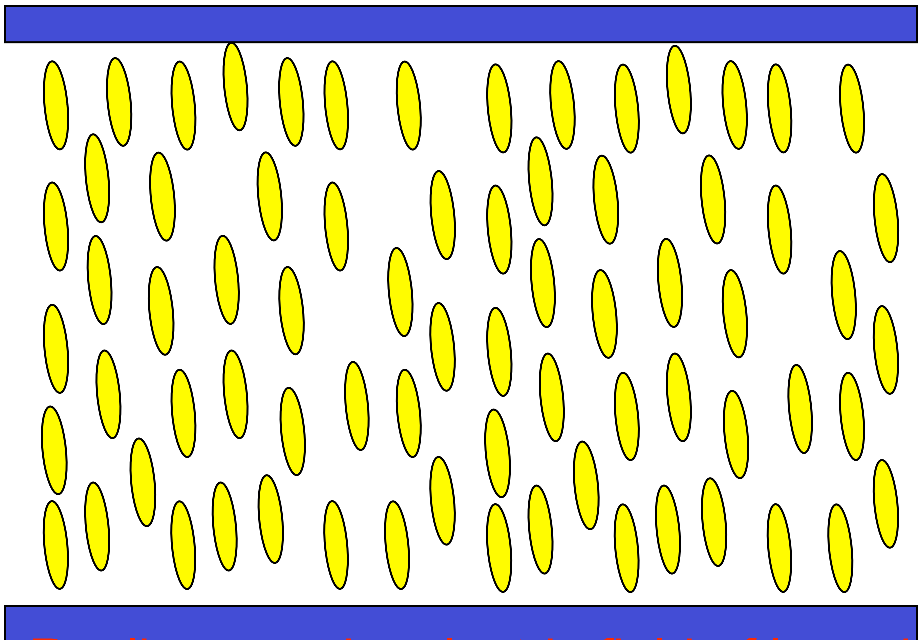
$$F_e = -\frac{\varepsilon_0}{2}\int_V \Delta\varepsilon(\vec{E}\cdot\hat{n})^2 dV$$

$$Intensity \sim E^2$$

→At optical frequencies $\Delta\varepsilon = n_e^2 - n_o^2$

Optically-induced molecular realignment

Once Laser is turned off –
realignment to uniform state



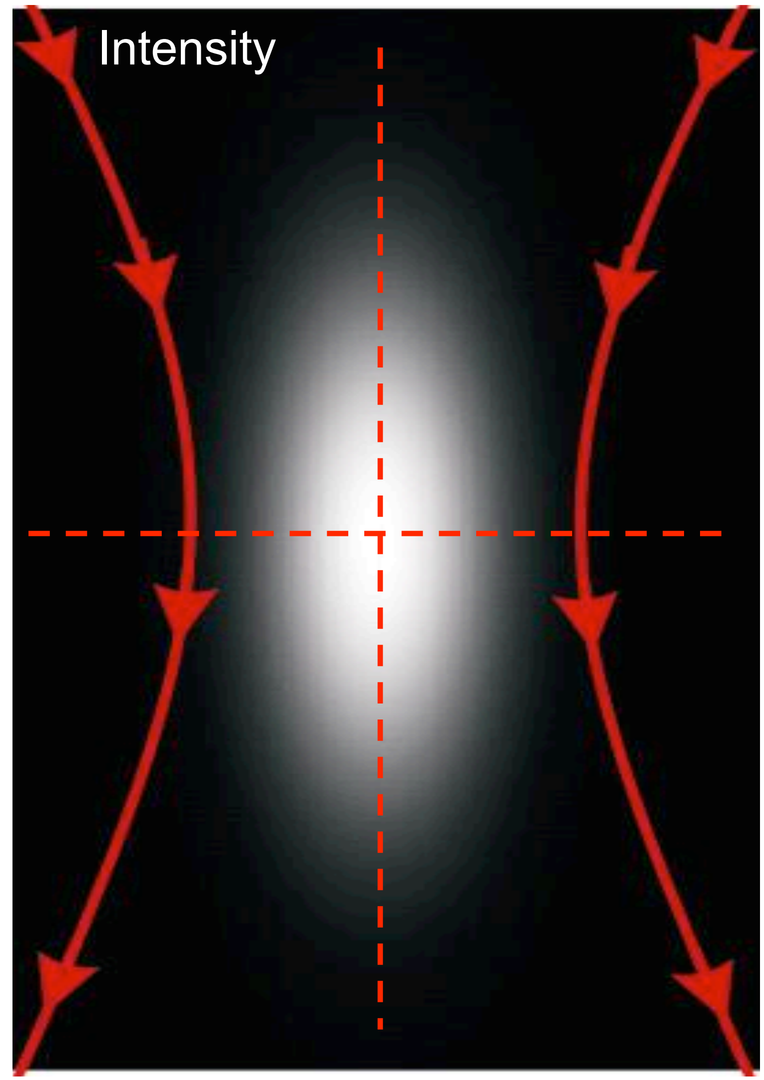
→Realignment by electric field of laser beam;

$$F_e = -\frac{\varepsilon_0}{2}\int_V \Delta\varepsilon(\vec{E}\cdot\hat{n})^2\, dV$$

→At optical frequencies $\Delta\varepsilon = n_e^2 - n_o^2$

Durbin, Arakelian, Shen, Phys. Rev. Lett. 47, 1411 (1981).

Focused Gaussian beam

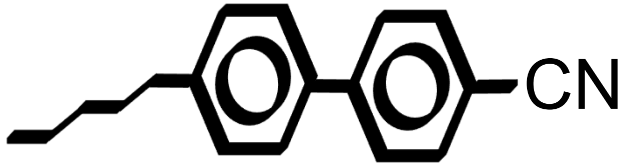


$$Intensity \sim E^2$$

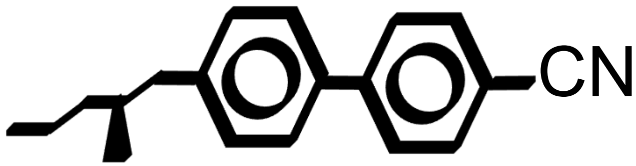
Chiral LCs: twisted ground states

Chiral & ordinary nematic LCs:

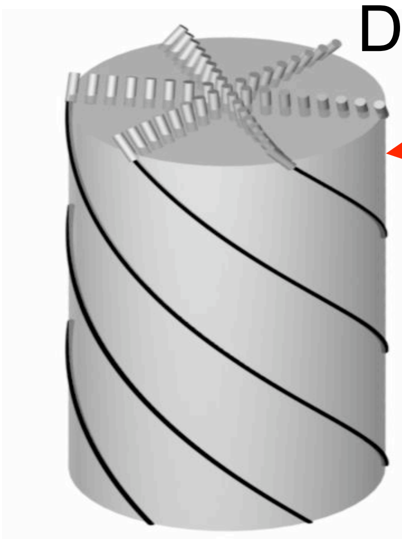
5CB



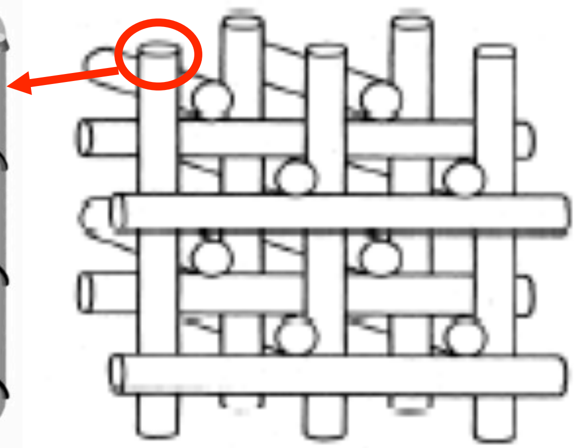
CB15



Blue phases



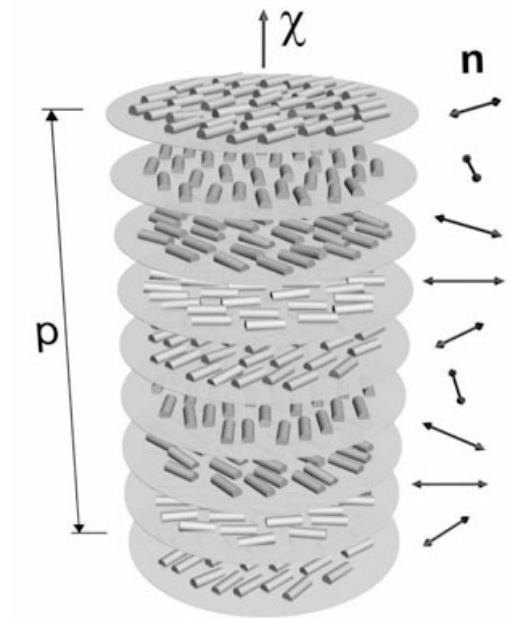
Double twist cylinders



Coles et al., *Nature* **436,** 997 (2005)

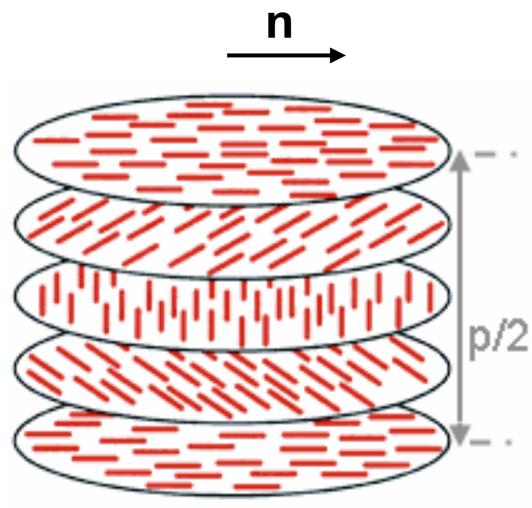
W. Cao et al., Nature Materials, 111, (2002).

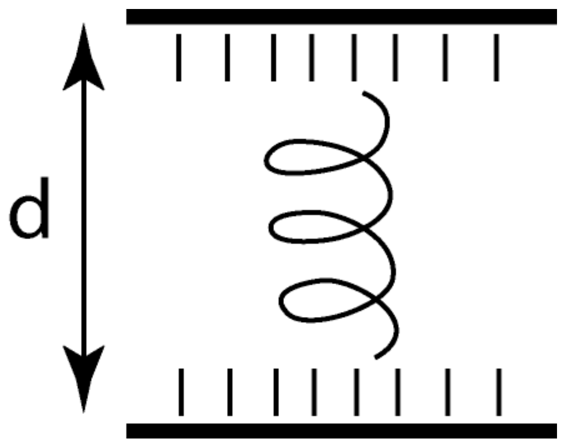
Cholesteric phases



Periodicity can be ~100nm

Chiral LC in a cell with vertical surface anchoring





→Structure characterized by its pitch p, the distance over which the director n rotates for 360°

→ Vertical boundary conditions are topologically incompatible with the helical structure

→Result - Frustration which has a tendancy to unwind the twisted structure
→Control parameter $C = d / p$

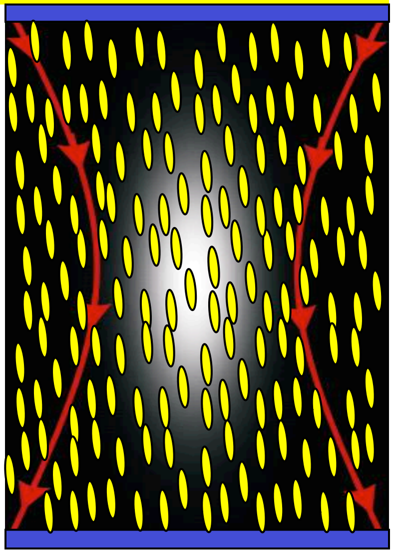
→ External electric field unwinds/winds the structure, depending on field direction;

P. Oswald et al., Phys. Rep. 337 (2000)…

Optical realignment: elastic and optical torques

Elastic free energy density for a nematic LC:

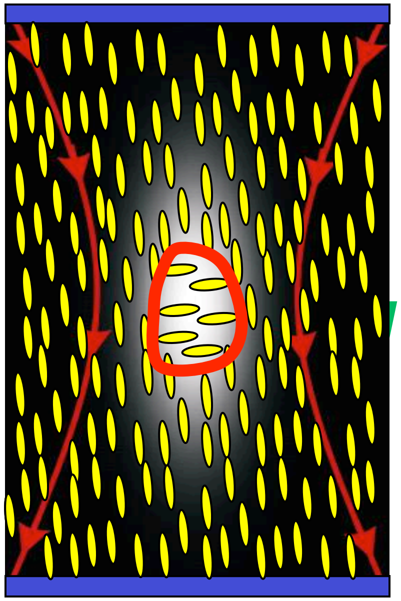
$$f_{elastic} = \frac{K_{11}}{2}(\nabla \cdot \hat{n})^2 + \frac{K_{22}}{2}[\hat{n} \cdot (\nabla \times \hat{n})]^2 + \frac{K_{33}}{2}[\hat{n} \times (\nabla \times \hat{n})]^2$$



→Electric free energy;

$$F_e = -\frac{\varepsilon_0}{2}\int_V \Delta\varepsilon (\vec{E} \cdot \hat{n})^2 dV$$

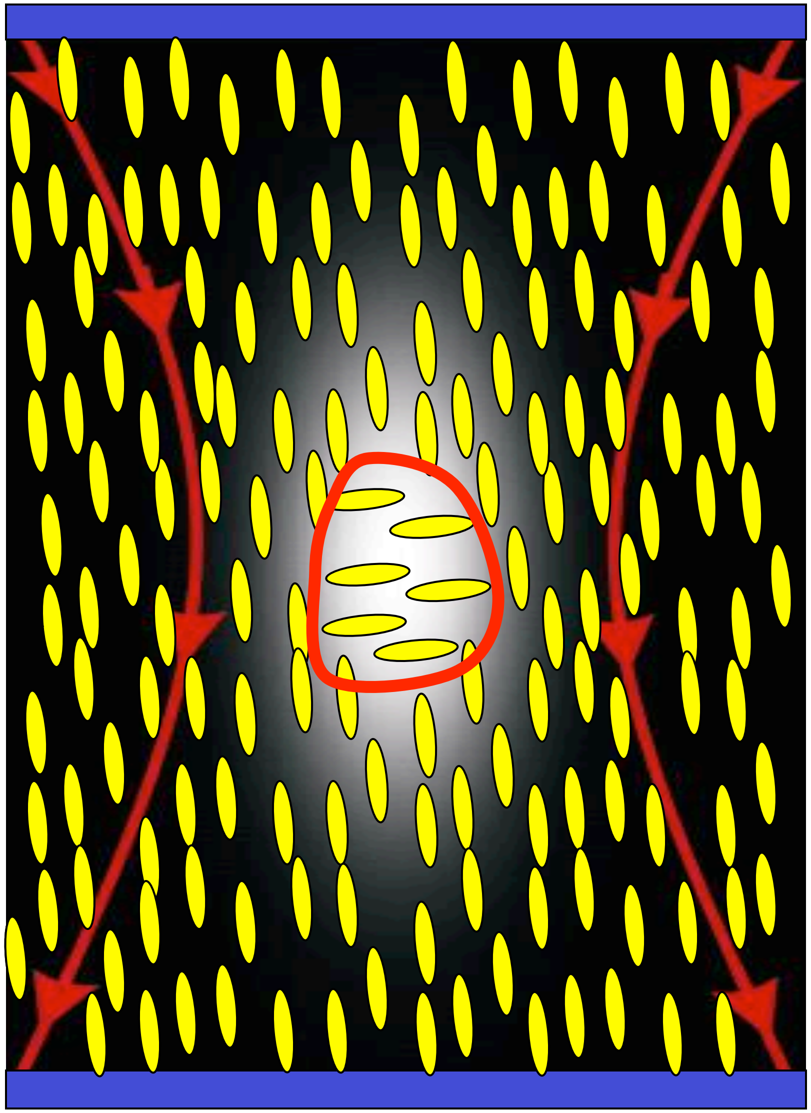
→At optical frequencies $\Delta\varepsilon = n_e^2 - n_o^2$



→Threshold Intensity – elastic and electric torques equal each other

Distortions in a homeotropic LC layer

→3D director field – no analytical results for thershold



Nematic:

→Threshold intensity is 2-20 times higher, but

$$I_{th} \propto \frac{K_{33}}{(n_e^2 - n_o^2)}$$

→Typical threshold powers ~ (40-200)mW

Chiral nematic:

→Threshold intensity for realignment:

$$I_{th} \propto \frac{K_{33}}{(n_e^2 - n_o^2)} \cdot \left(1 - 4\frac{d^2}{p^2}\frac{K_{22}^2}{K_{33}^2}\right)$$

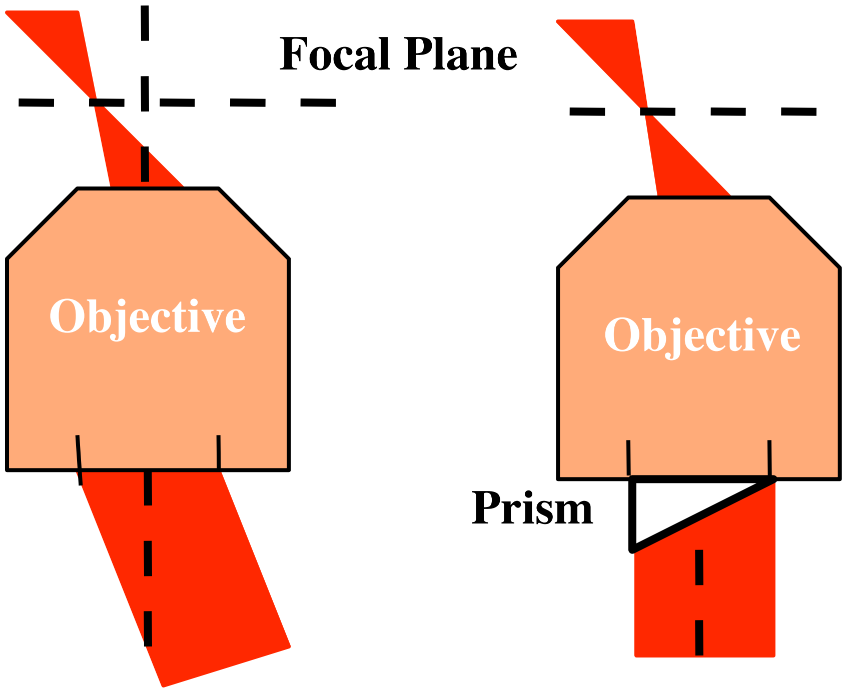
→Chiral LCs are realigned @ lower laser power

→Threshold power can be very small, ~10mW

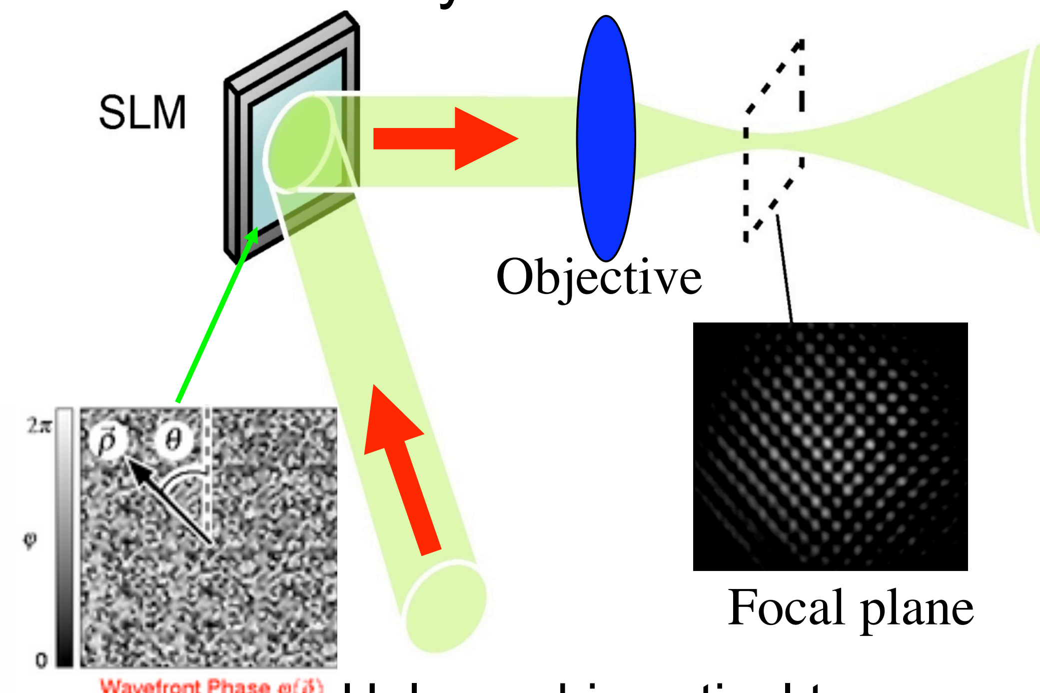
→Waist ≤ cell thickness, ***w* ≤ *d***

Beam steering and shaping using LC spatial light modulators

Equivalent ways of steering

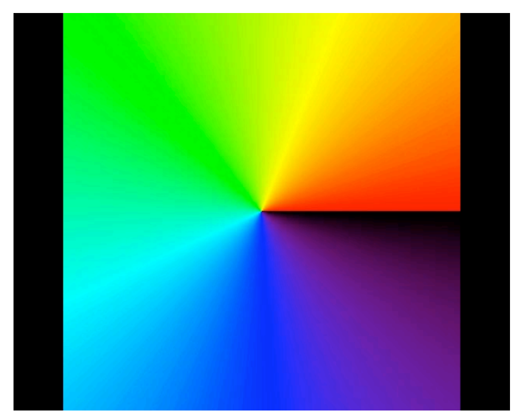


Phase-only LC SLM



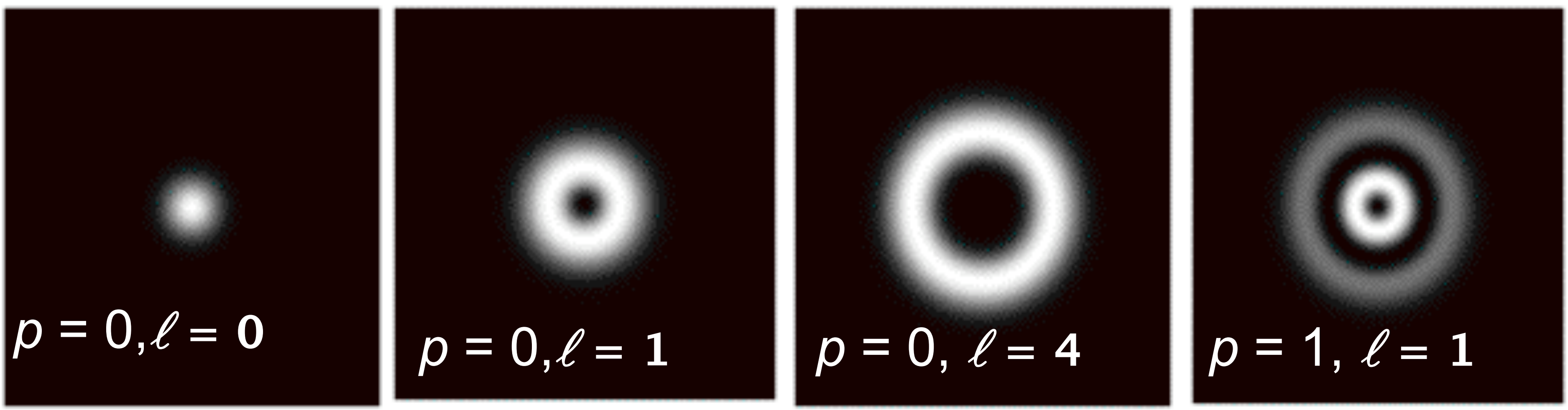
Holographic optical tweezers

Optical Vortex hologram: here color represents *phase*, which is a periodic variable (0 - 2π) so the horizontal line is *not* a discontinuity.



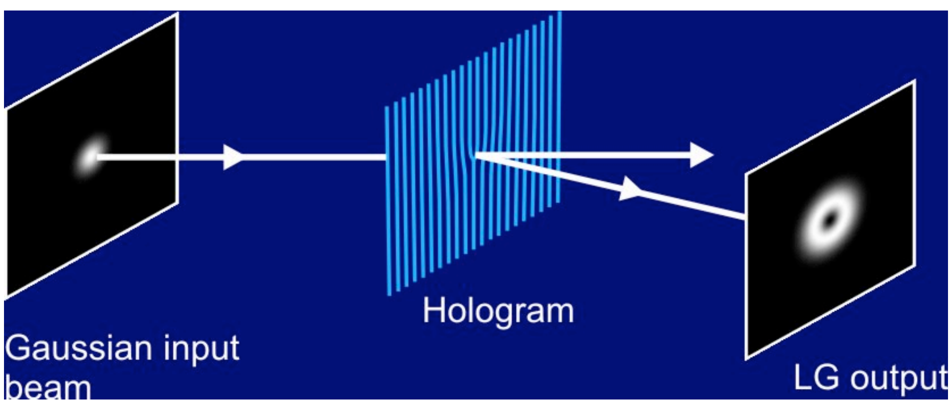
Laguerre-Gaussian modes: an optical vortex

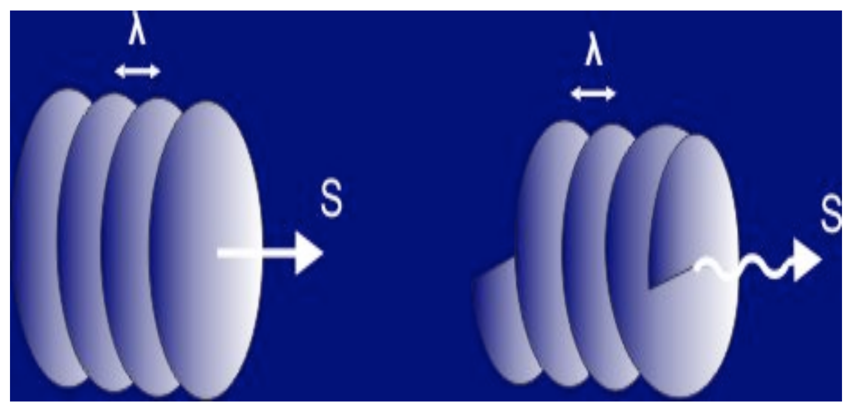
SLM also allows for easy creation of Laguerre-Gaussian beams



– **radial mode index *p* & azimuthal mode index *l***

•Screw dislocations in the phase of light
•Can be generated by dislocations in gratings

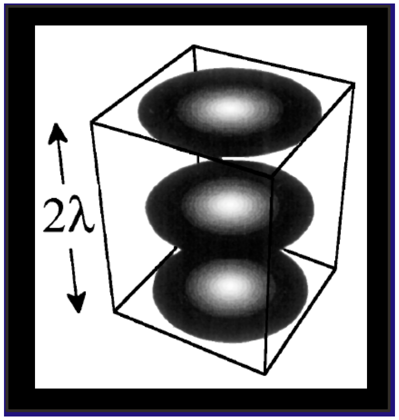




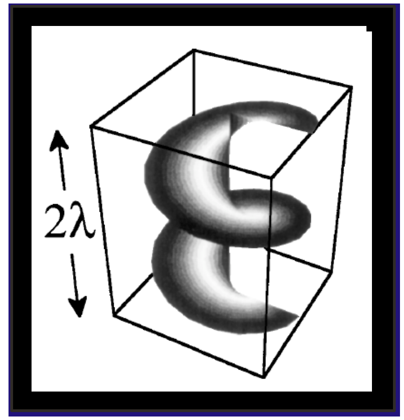
*L. Allen et al., PRA **45**, 8185 (1992)*

Laguerre-Gaussian beams

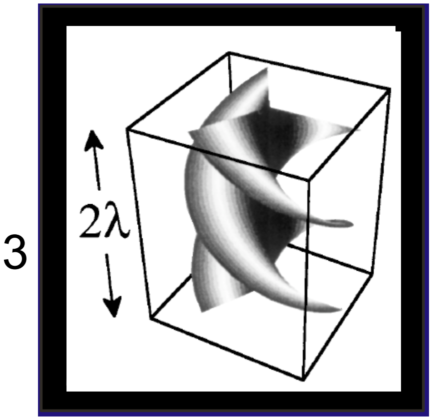
l = 0

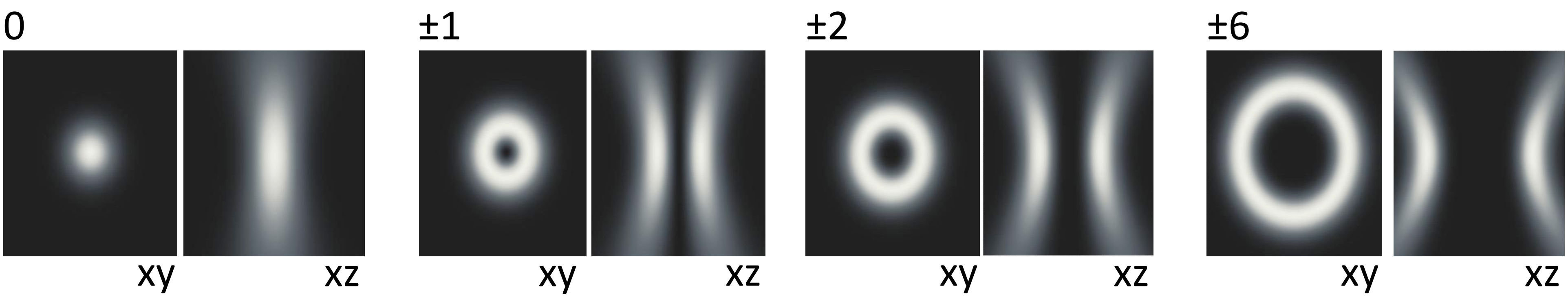


l = 1



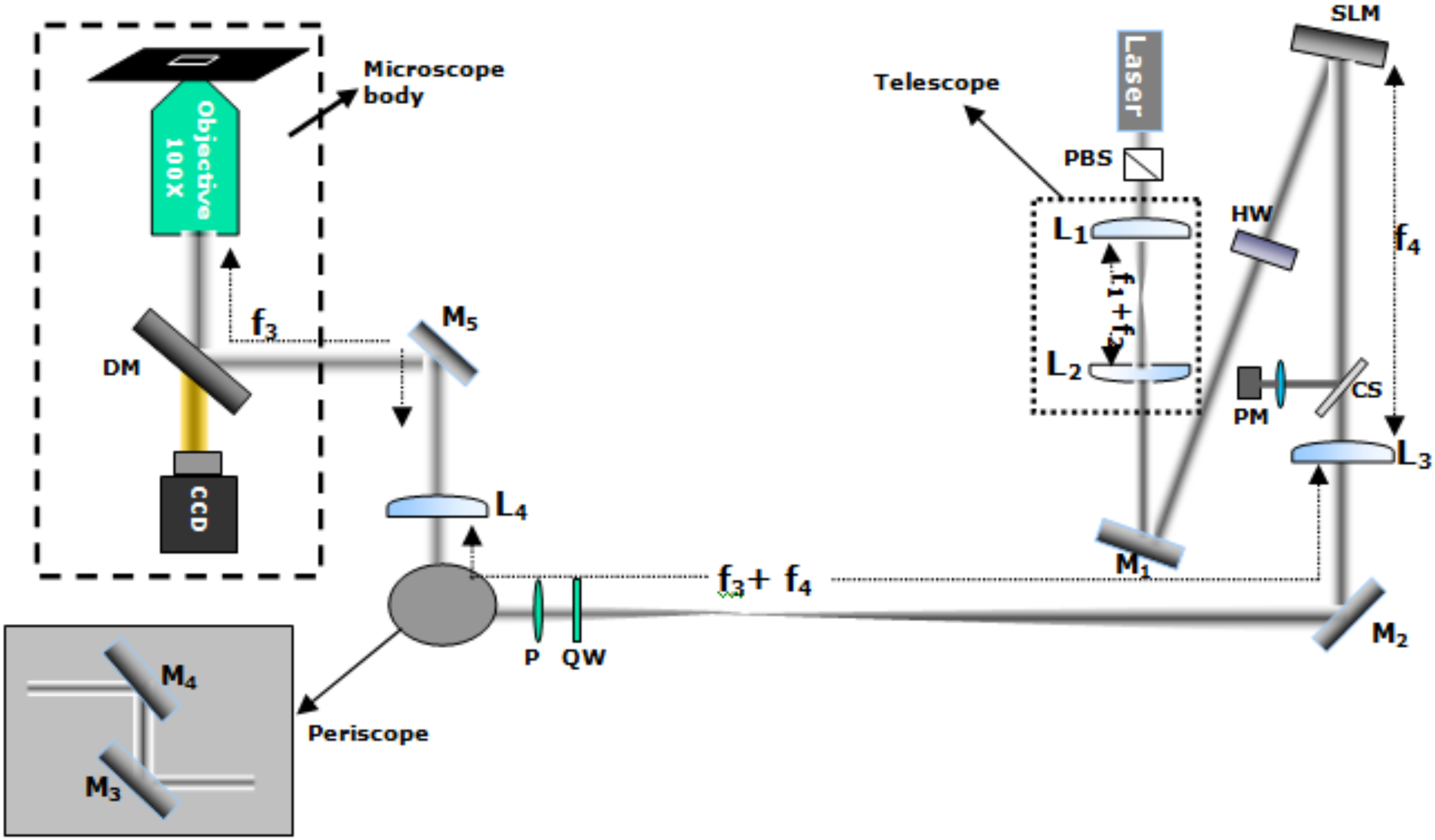
l = 3





J. Courtial et al., PhysRevLett 80, 3217, 1998

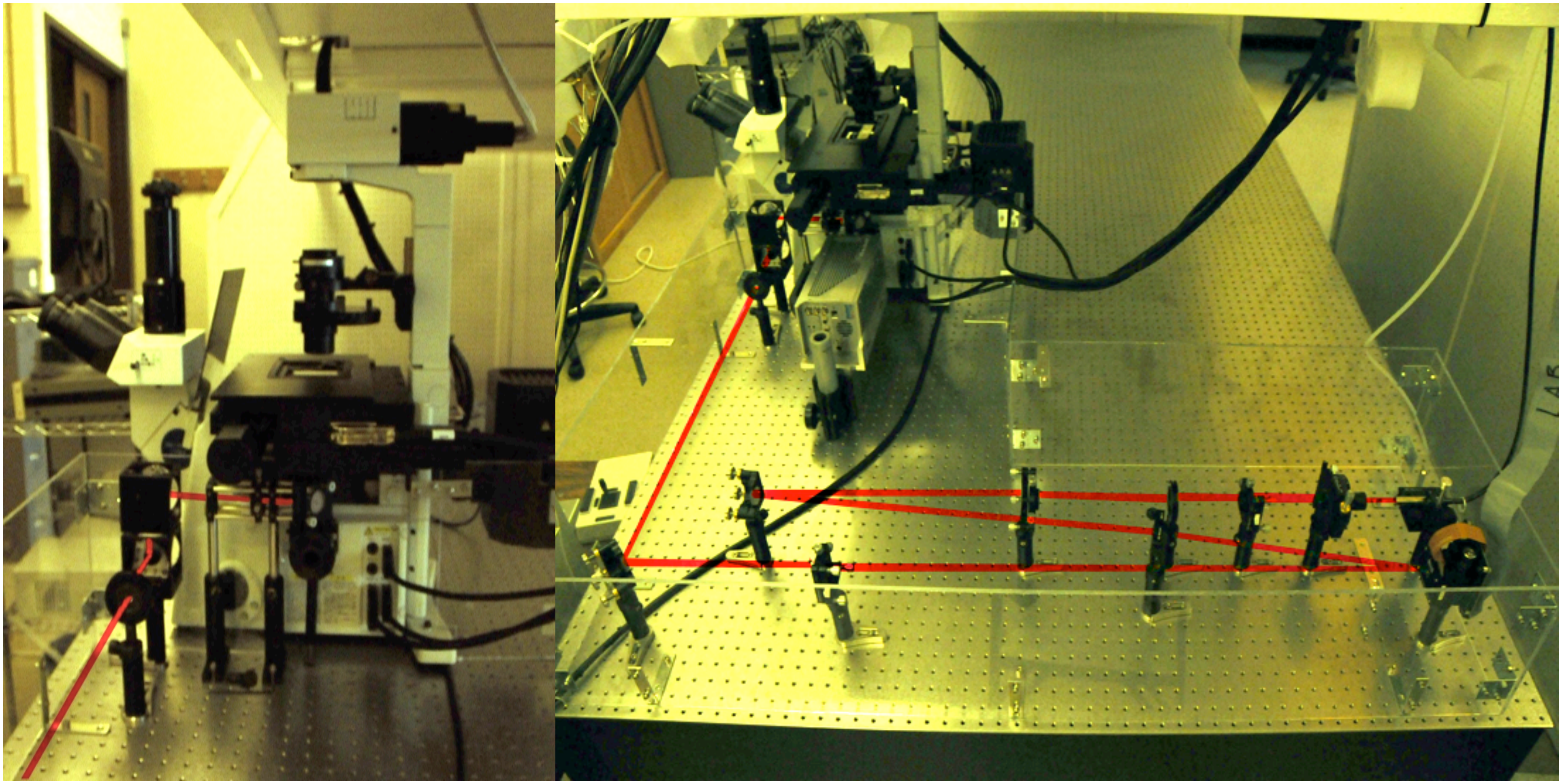
Holographic optical trapping setup



•Phase profiles in this setup obtained using the phase-only LC SLM
•Laser trapping beam at 1064nm, Ytterbium-doped fiber laser (IPG Photonics)

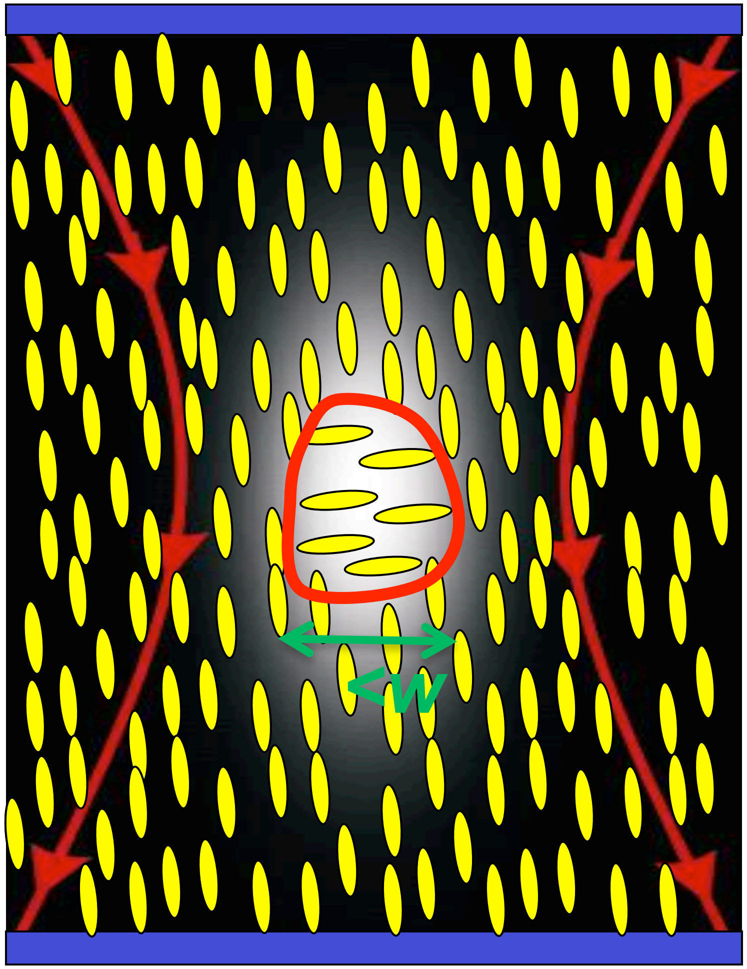
Holographic laser manipulation set up

IX81 Inverted OpticalMicroscope (Olympus)
Laser: IPG Photonics, IR (1064nm)
SLM: From Boulder Non Linear Systems (BNS)
High-speed camera (0.5 million frames per second).

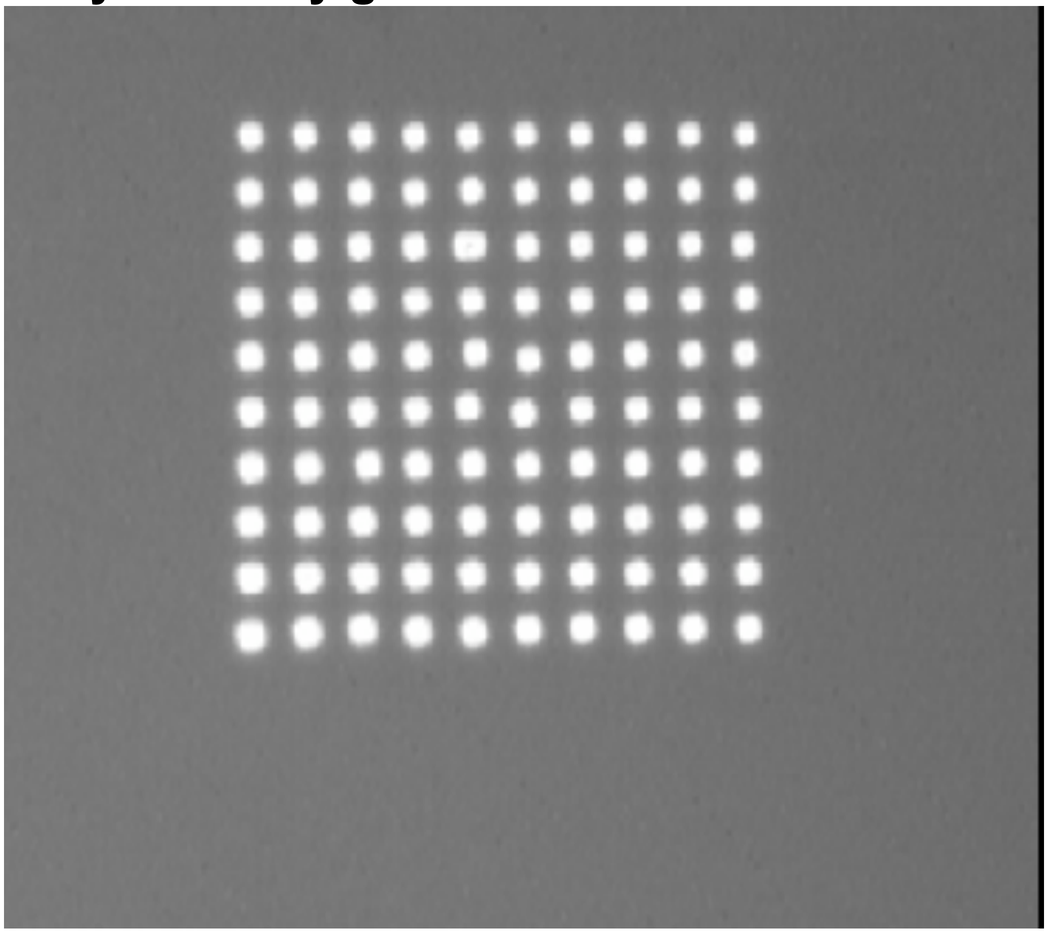


Setup in the lab

Dynamically generated distortions in a nematic LC

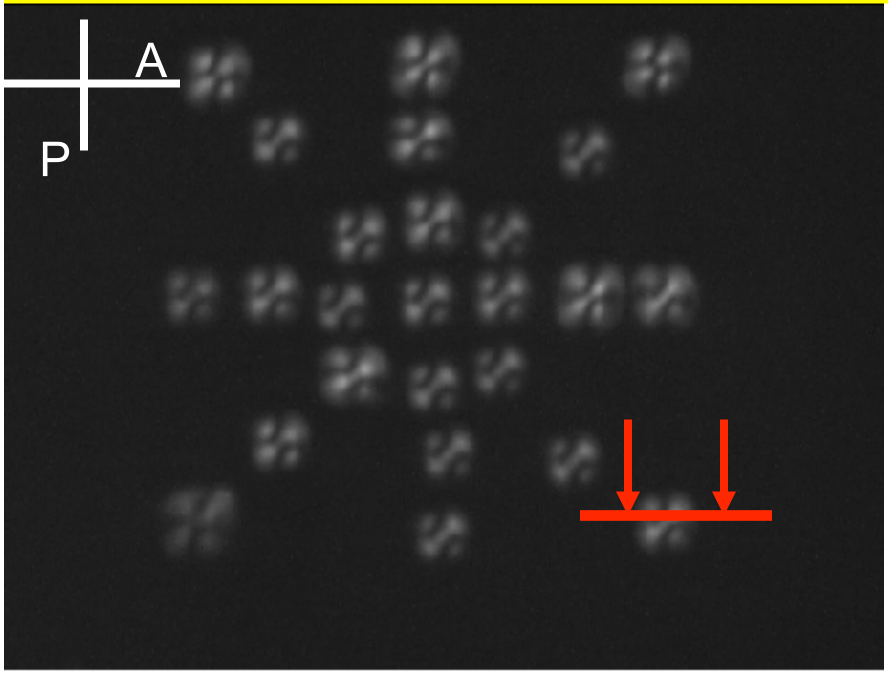


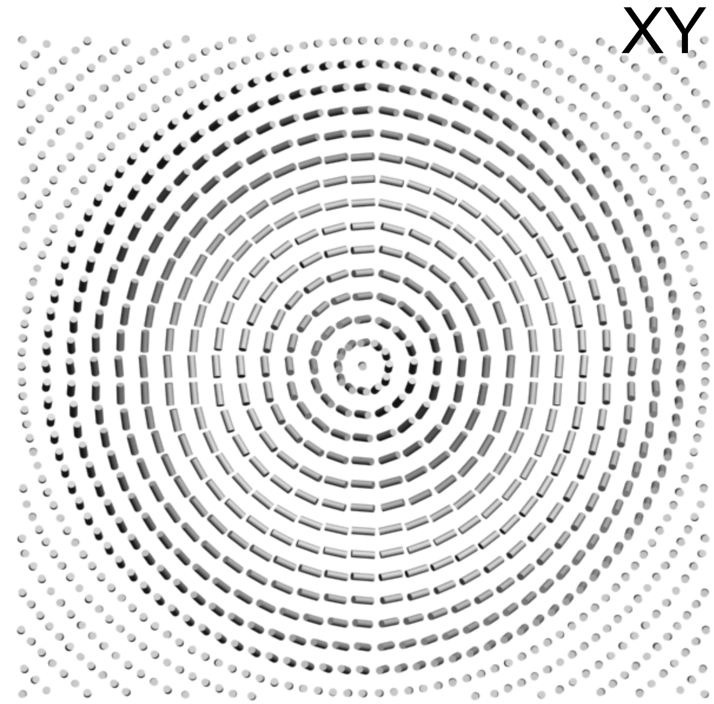
Dynamically generated



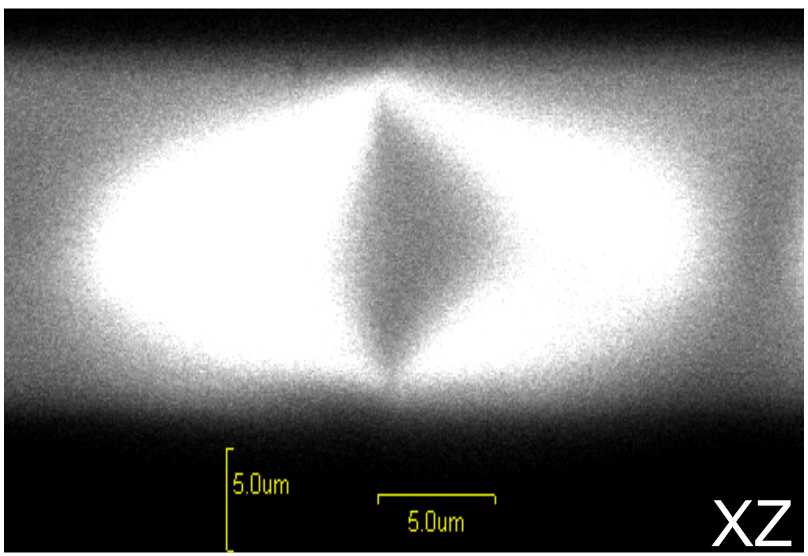
→Generated by laser CW Nd: YAG, 1064nm;
→Threshold effect;
→Distortion size can be lower than the beam waist;
→Distortions disappear after laser is switched off of shifted away;
→Realignment/relaxation times (5-100)ms;

Optically-generated stable structures in chiral LC

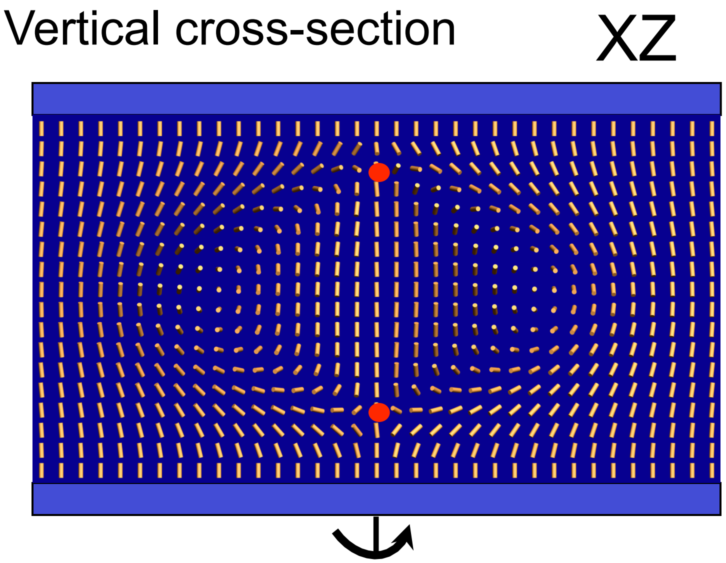




Confocal vertical cross-section



Vertical cross-section



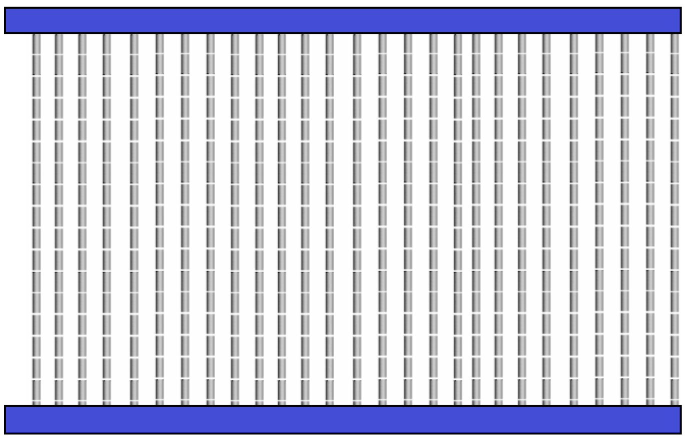
Twist vs. no twist in frustrated cholesteric cell

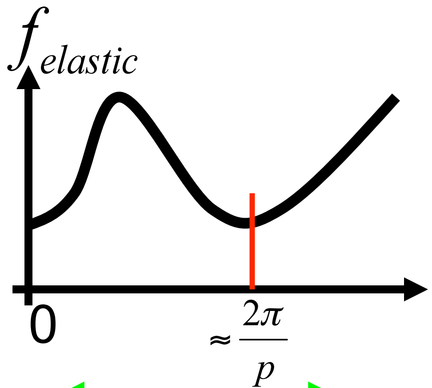
Splay Twist Bend Saddle-splay

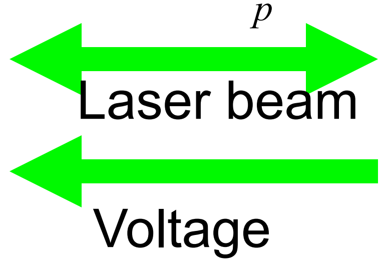
$$f_{elastic} = \frac{K_{11}}{2}(\nabla\cdot\hat{n})^2 + \boxed{\frac{K_{22}}{2}\left[\hat{n}\cdot(\nabla\times\hat{n}) + \frac{2\pi}{p}\right]^2} + \frac{K_{33}}{2}[\hat{n}\times(\nabla\times\hat{n})]^2 \boxed{+ f_{24}}$$

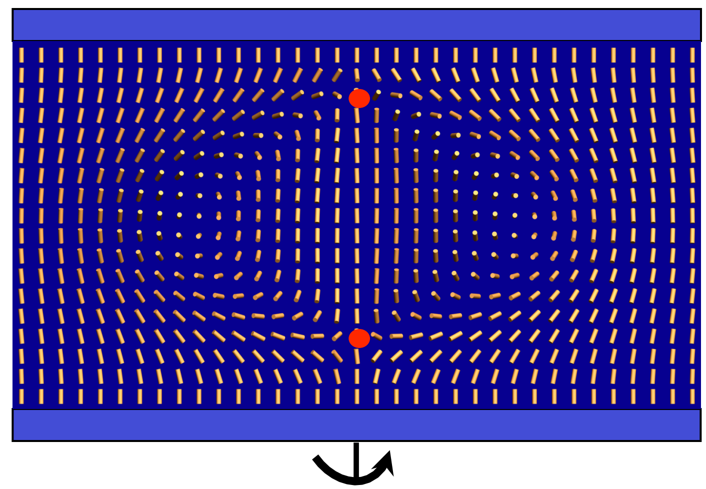
$$f_{24} = -K_{24}\{\nabla\cdot[\hat{n}(\nabla\cdot\hat{n}) + \hat{n}\times(\nabla\times\hat{n})]\}$$

Untwisted cholesteric cell









→ Cholesteric pitch *p~d*;

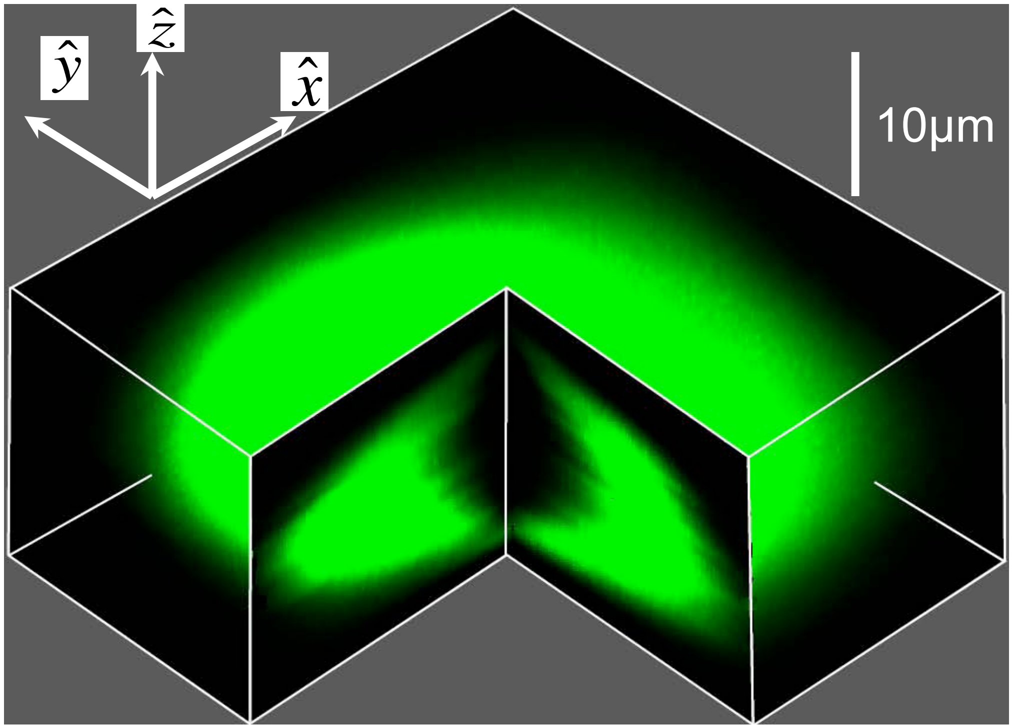
→ Strong energetic barrier between the structures >> $K_B T$;

→ Both states can be stable for long time;

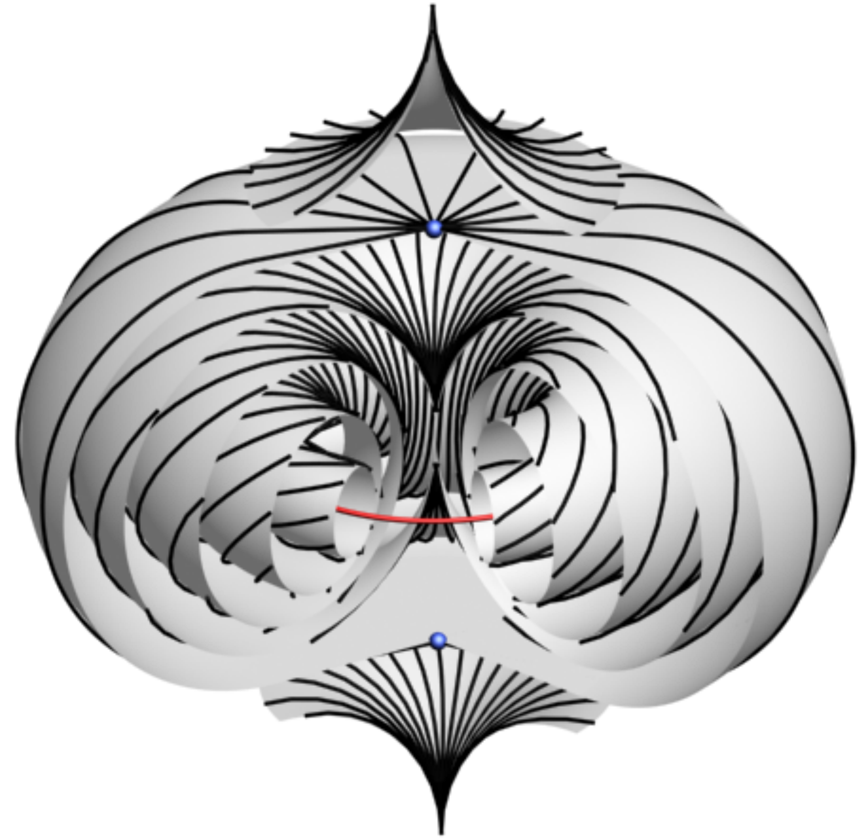
→ Switching by a focused laser beam or applying voltage;

3D imaging & reconstruction of 3D director field

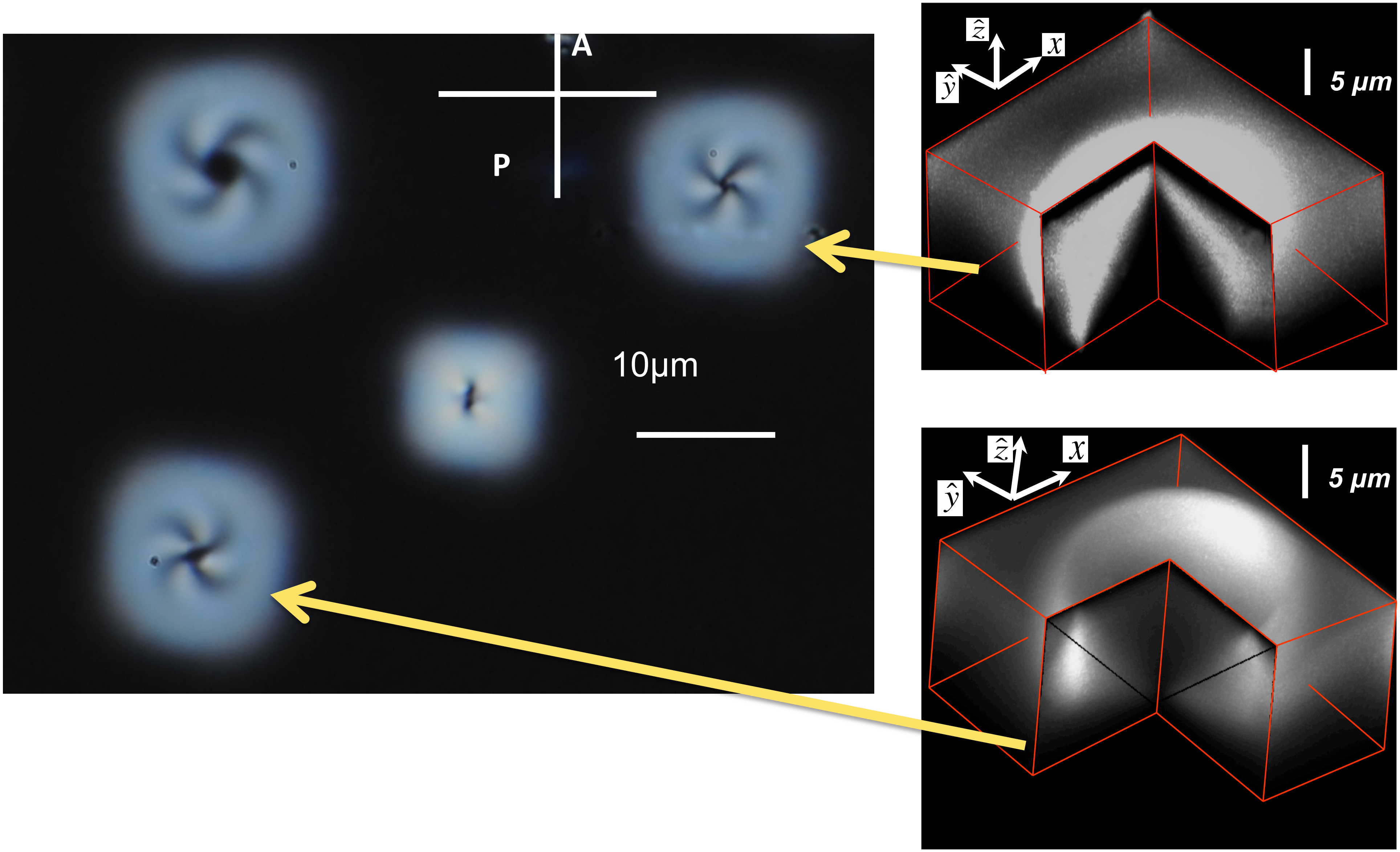
3D image



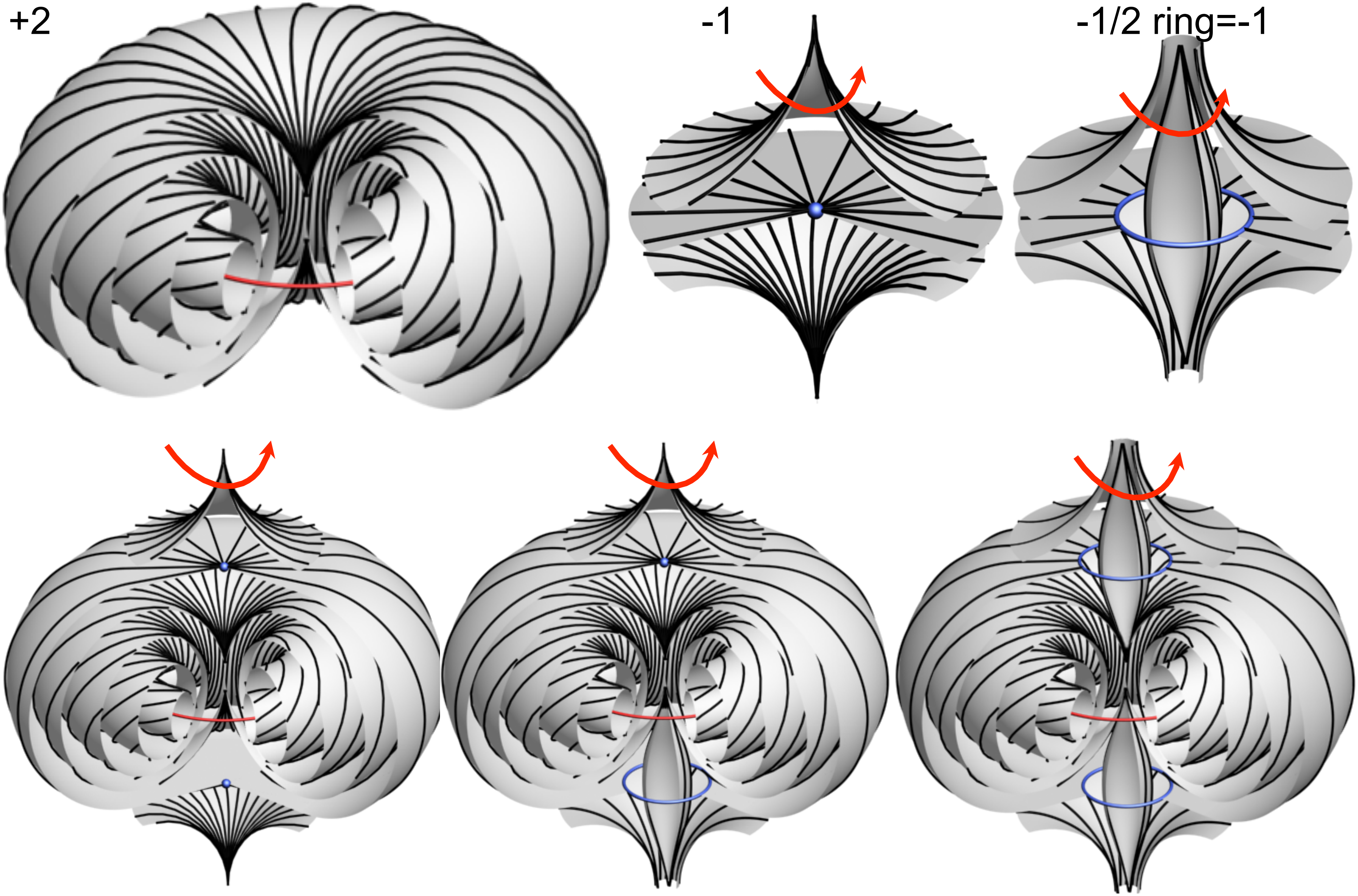
Reconstructed 3D structure



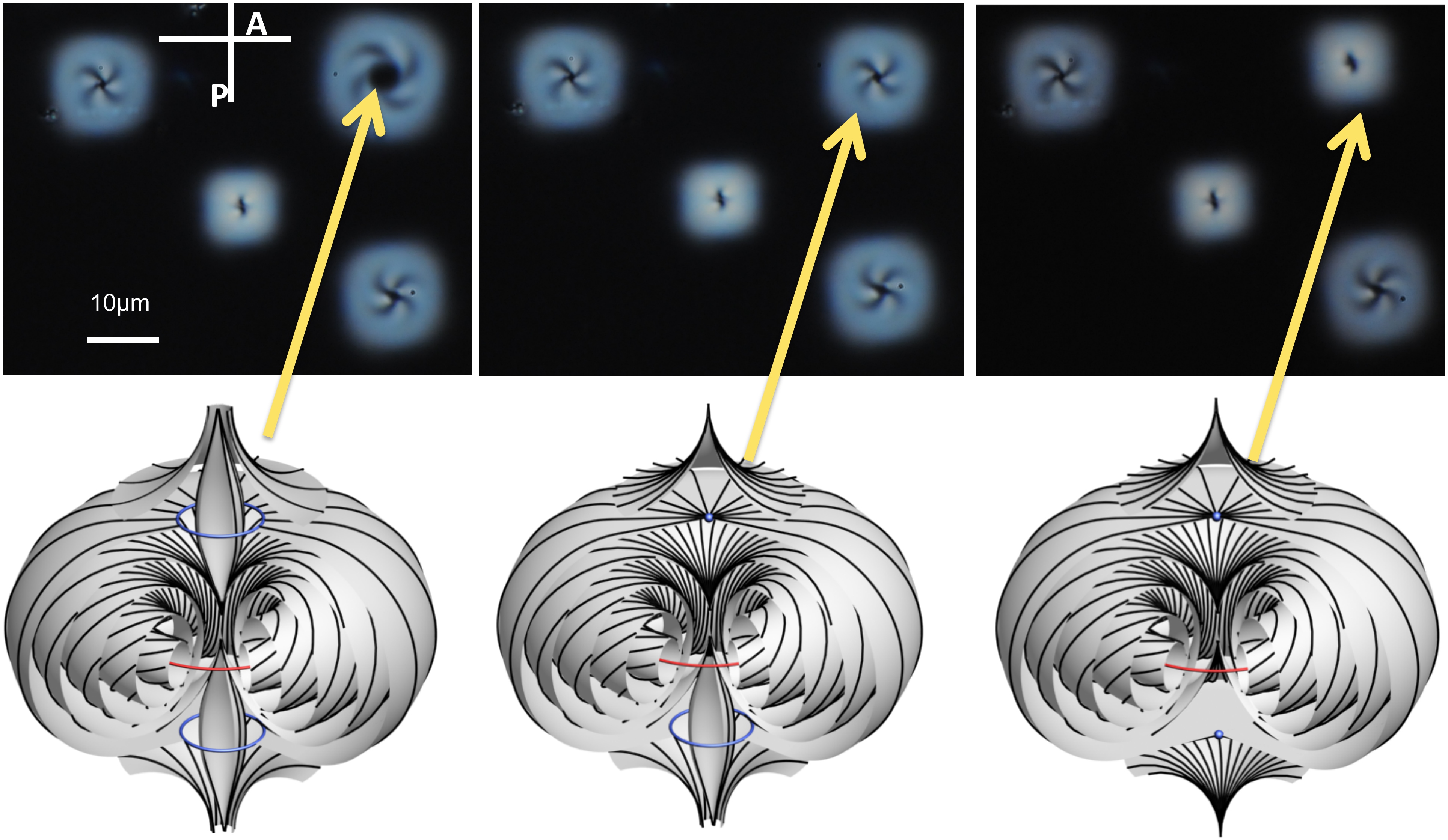
Optically-generated stable structures in chiral LC



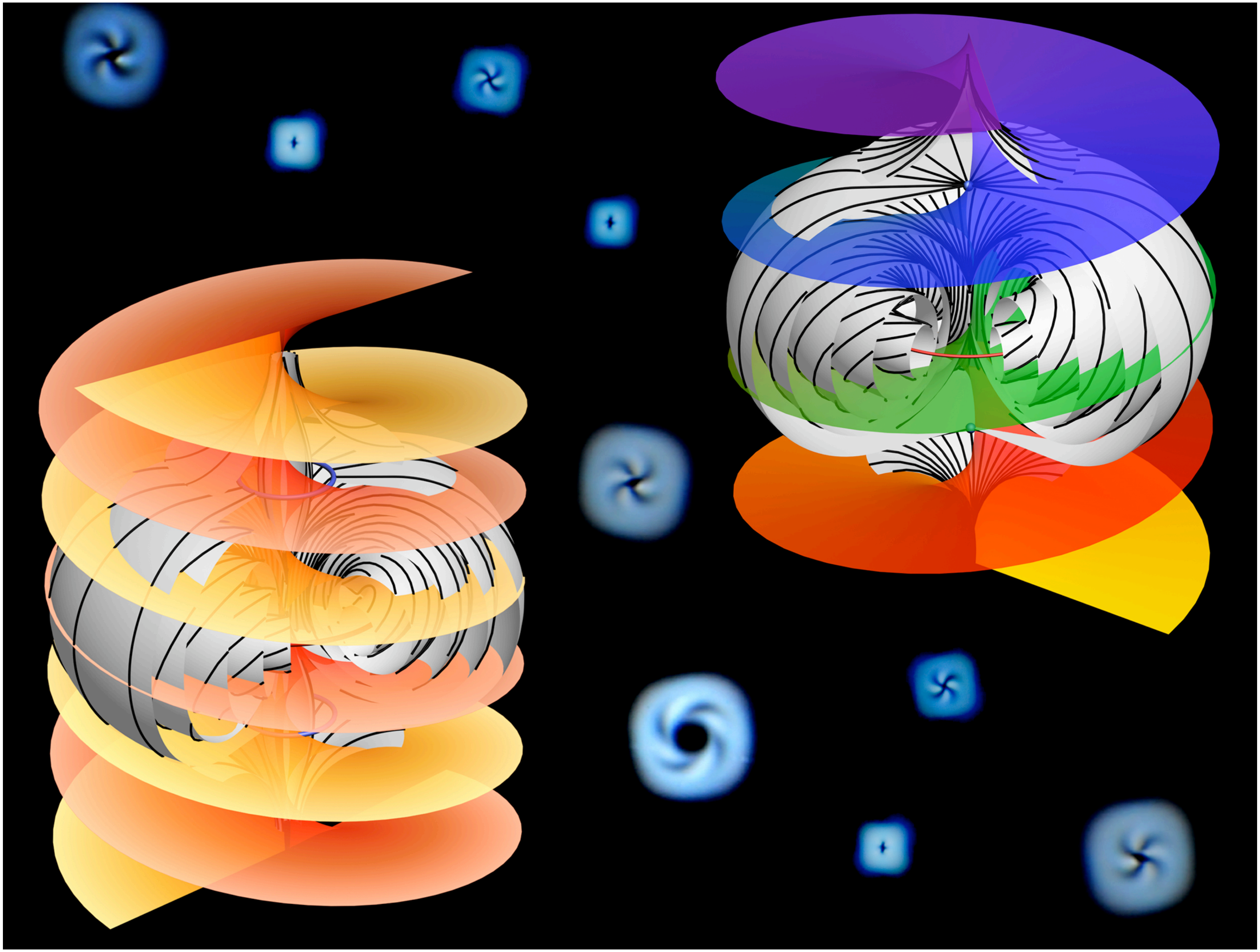
Types of LG-beam-generated TORON structures



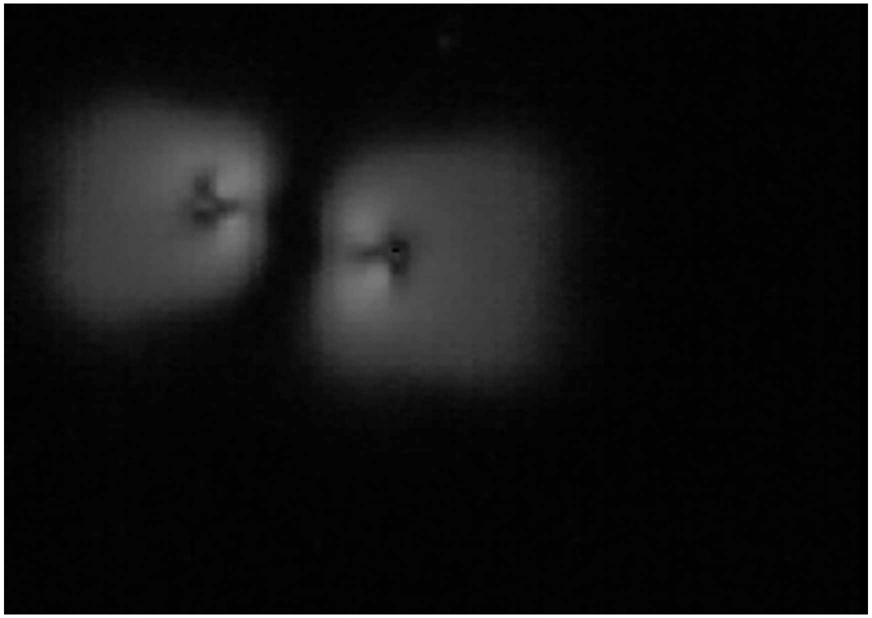
Optical control of defects in Torons

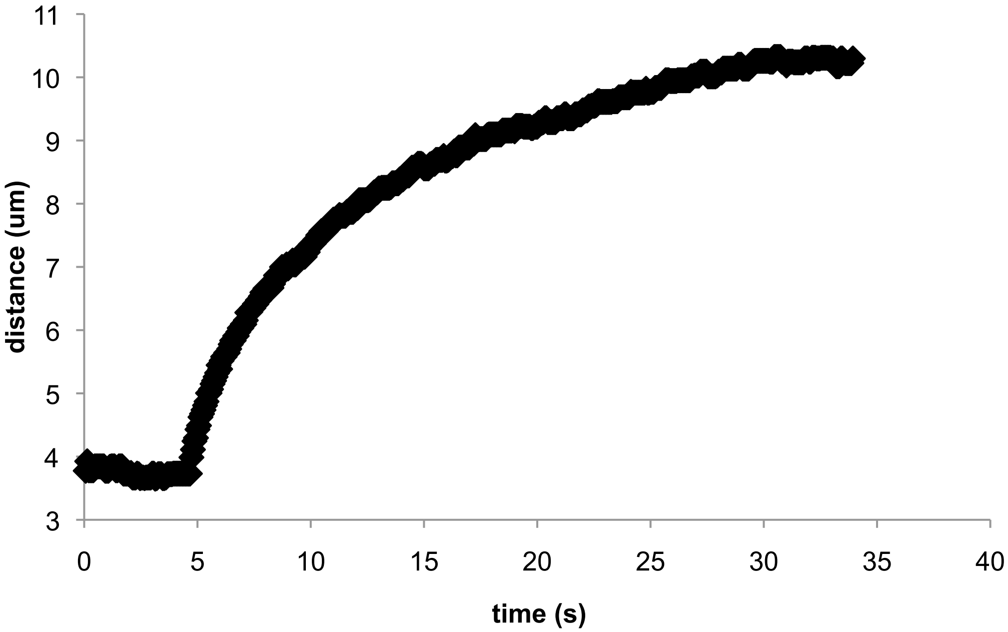


Control of defects in LCs using optical singularities



Torons interact via short-range repulsive elasticity-mediated interactions

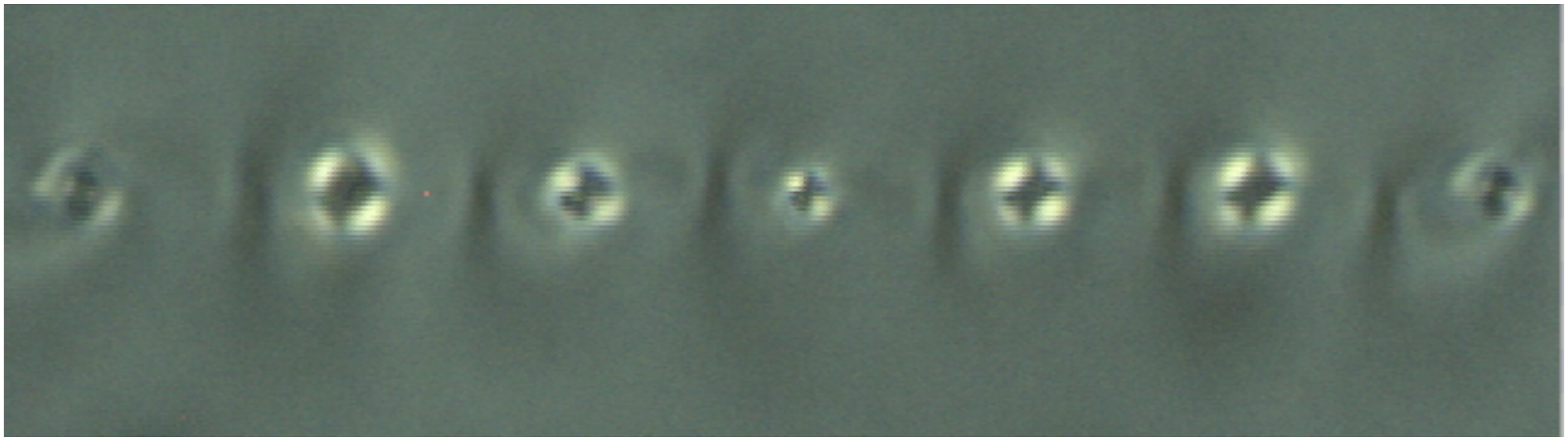




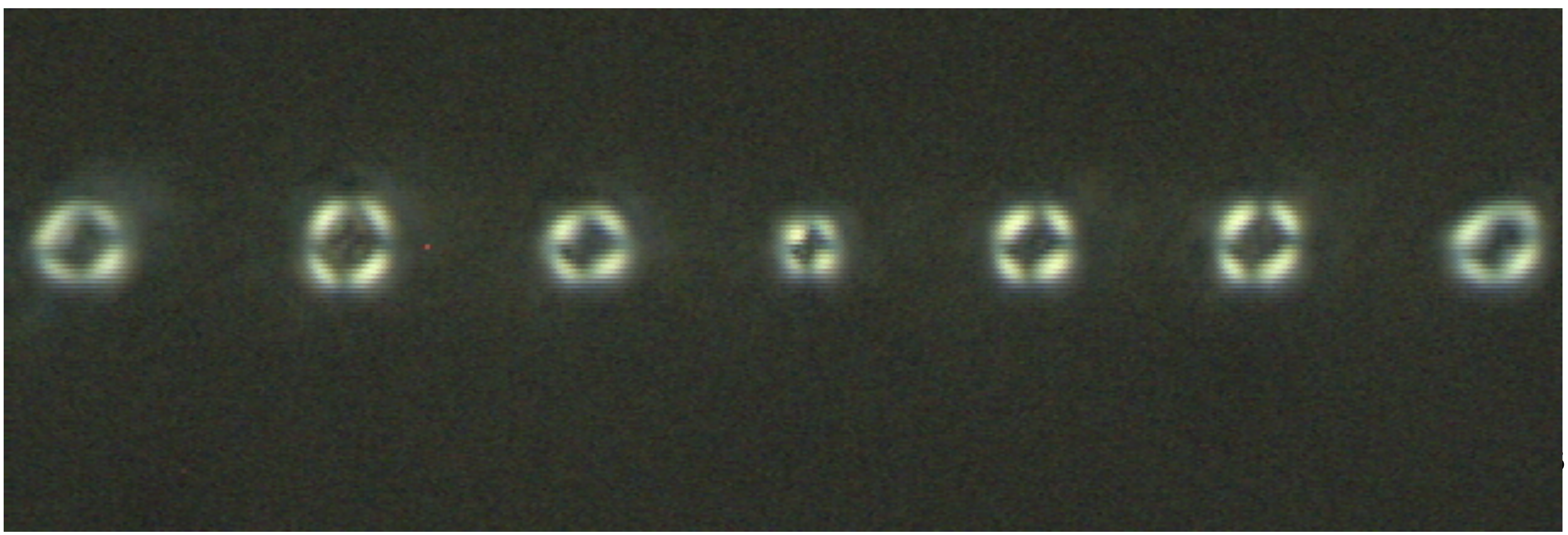
→Interactions can be screened or enhanced by applying external fields;

Toron-Umbilical pairs forming chains in applied field (negative dielectric anisotropy)

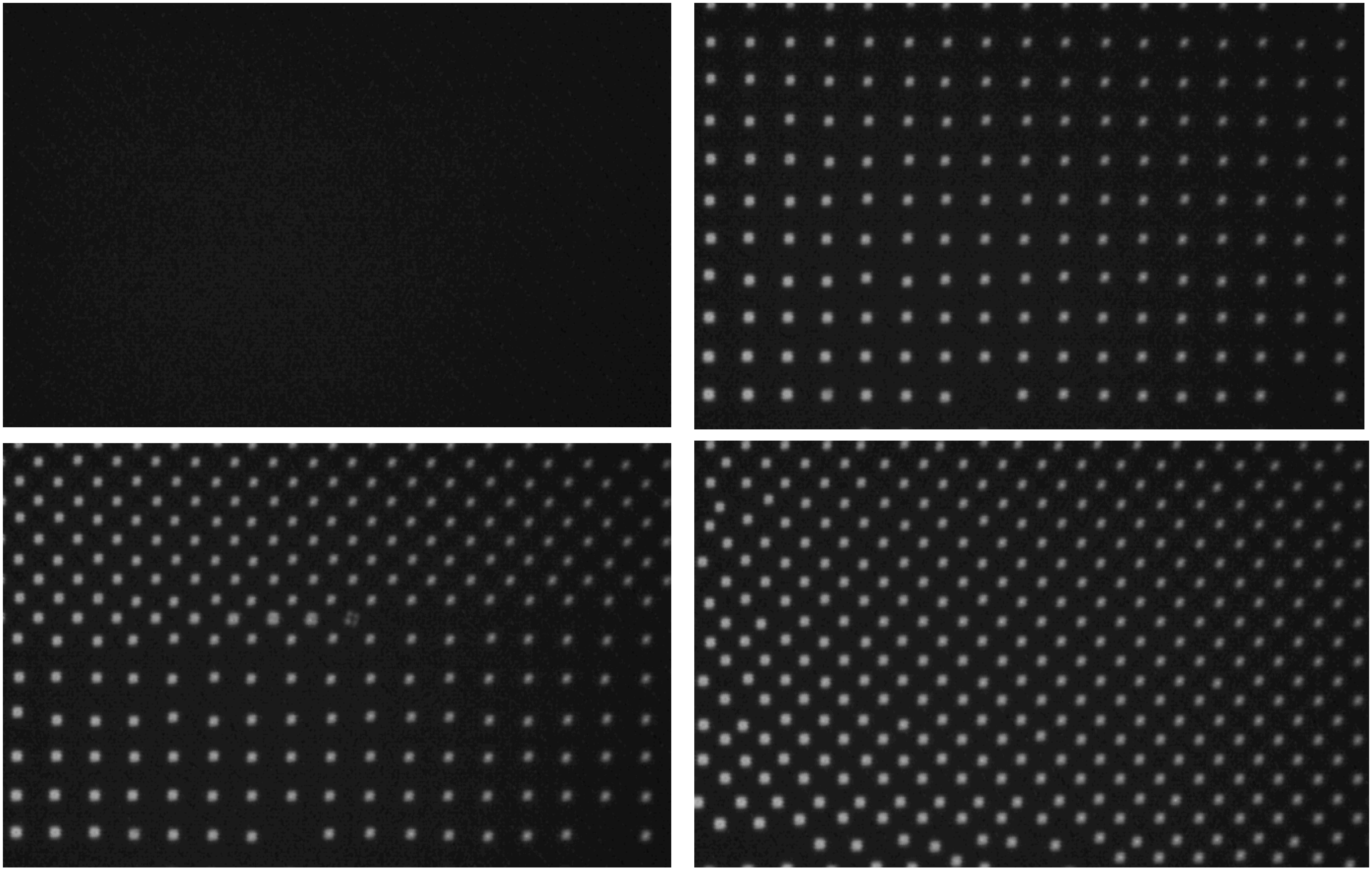
→Assembled at applied voltage: Umbilics appear and C-vector field is dipolar



→Voltage turned off

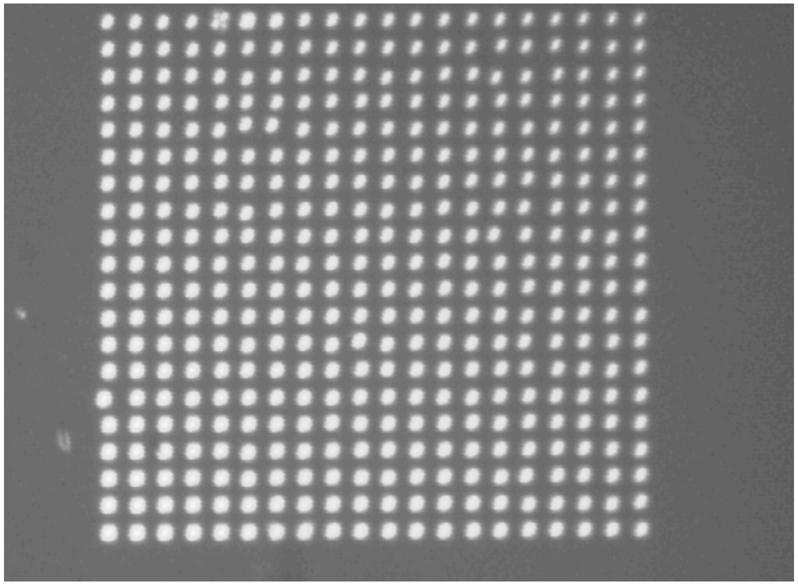


Laser-generated multistable structures

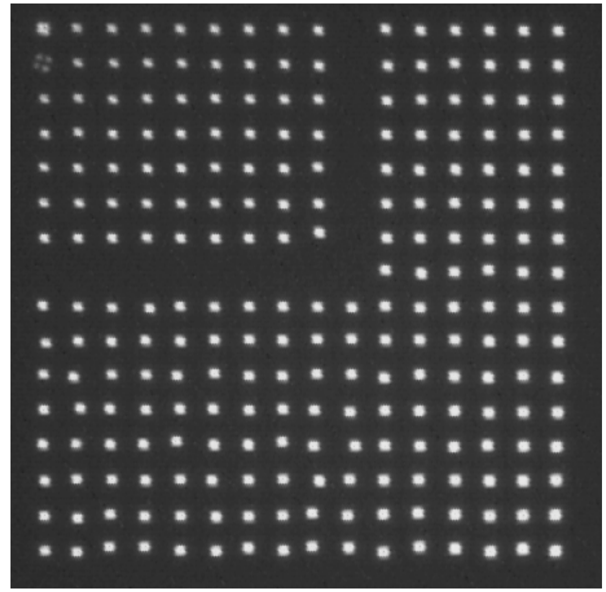


Laser-generated multistable structures

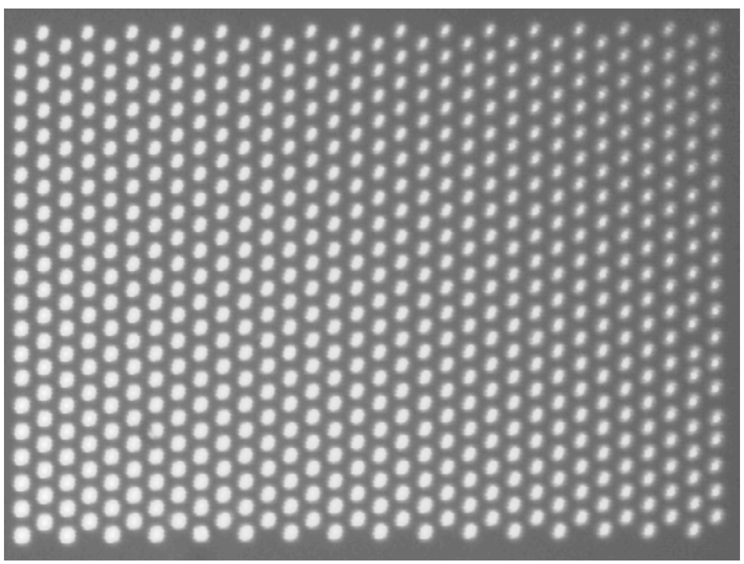
Square-periodic



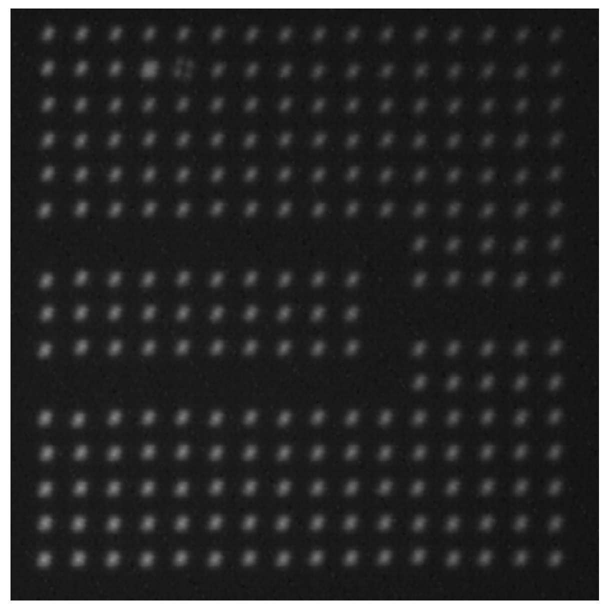
Square-periodic with channels



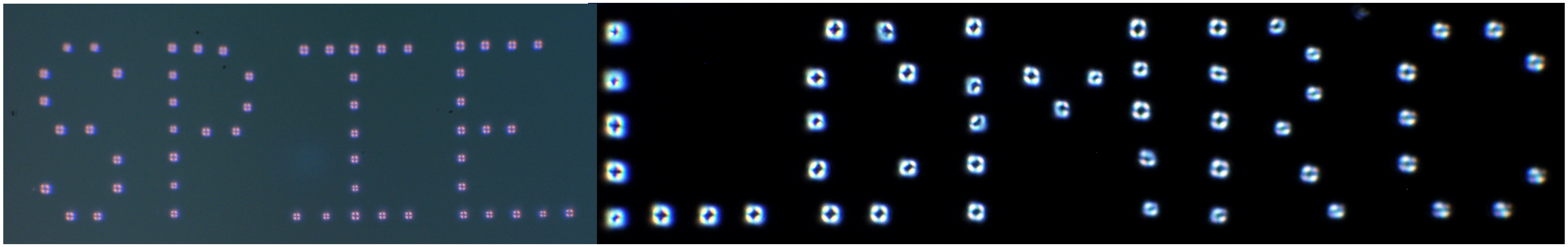
Hexagonal arrays

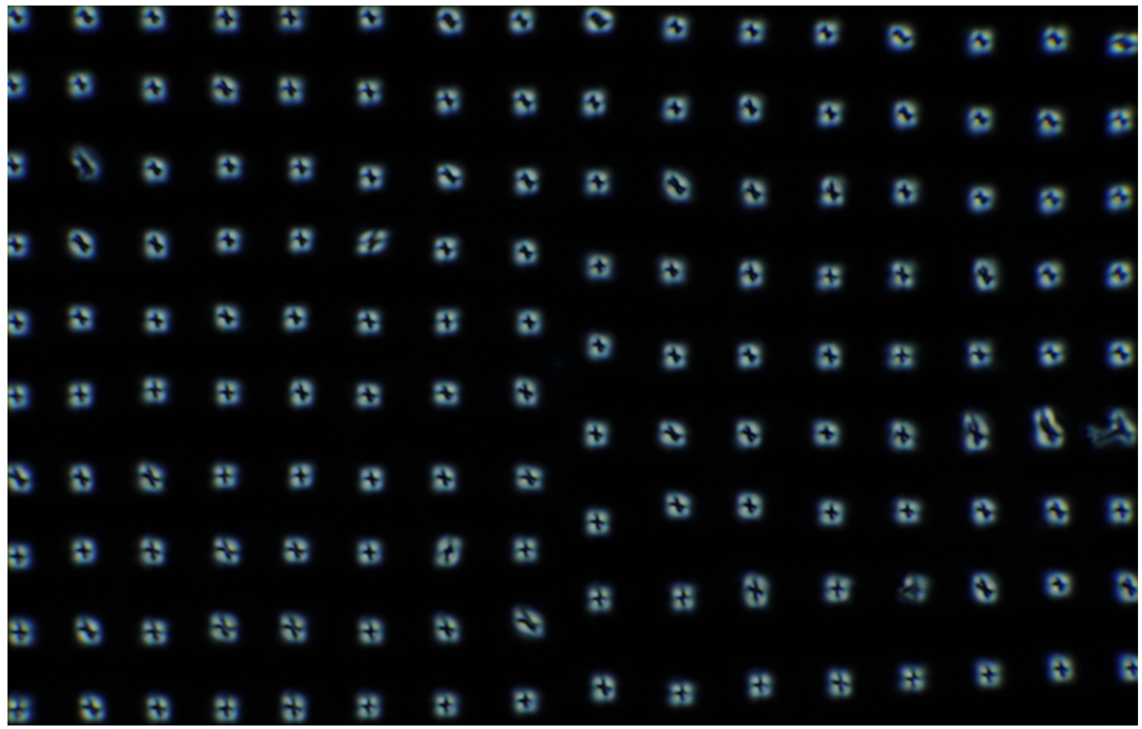


Square-periodic with channels



Laser-generated multistable structures

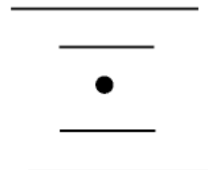
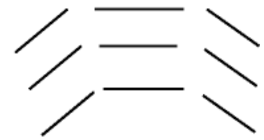




Modeling of frustrated chiral LC structures

Frank elastic energy

$$f_0 = K_{11}(\nabla \cdot \mathbf{n})^2 + K_{22}(\mathbf{n} \cdot \nabla \times \mathbf{n} + 2\pi/p)^2 + K_{33}(\mathbf{n} \times \nabla \times \mathbf{n})^2$$

splay  *twist*  *bend* 

$$f_{24} = -K_{24}\nabla \cdot (\mathbf{n}\nabla \cdot \mathbf{n} + \mathbf{n} \times \nabla \times \mathbf{n})$$

saddle-splay

$$f_{\text{elec}} = -\frac{1}{2}\epsilon_0 \Delta\epsilon (\mathbf{E} \cdot \mathbf{n})^2$$

electric field

$$f_{\text{Frank}} = f_0 + f_{24} + f_{\text{elec}}; \qquad F_{\text{Frank}} = \int f_{\text{Frank}} dV$$

Dynamics and minimisation (relaxation method) using finite difference method (4th order) in 3D (and also 2D) on a N1 x N2 x N3 cubic lattice

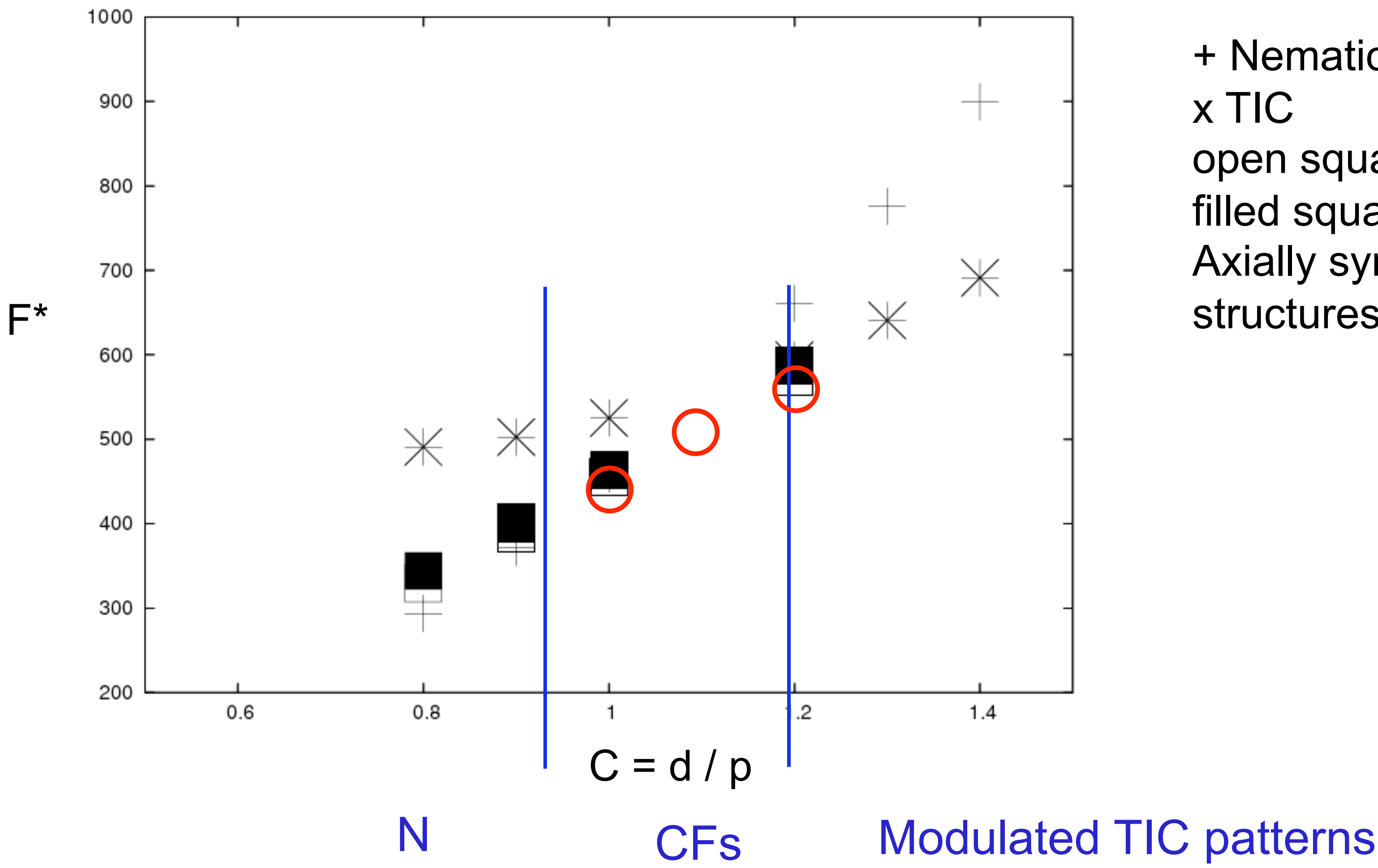
$$\frac{\partial n_i}{\partial t} = -\frac{\delta F}{\delta n_i}; \quad i = 1, 2, 3 \qquad n_i \longleftarrow n_i - ht\frac{\delta F}{\delta n_i}$$

Used parameters:

K_{11} = 14.1 pN; K_{22} = 6.7 pN; K_{33} = 15.5 pN; $K_{24} = K_{22}$; $\Delta\varepsilon$ = 3.4

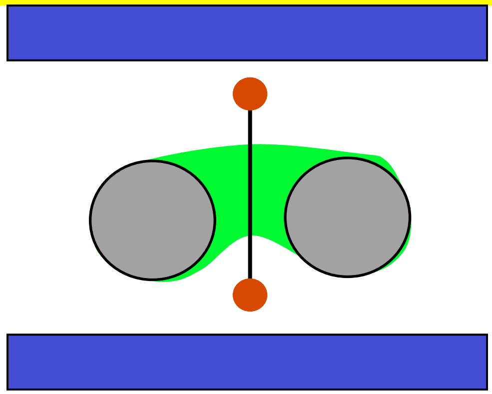
N1 = N2 = 119, N3 = 35 or 71

Free energy of localized chiral LC structures

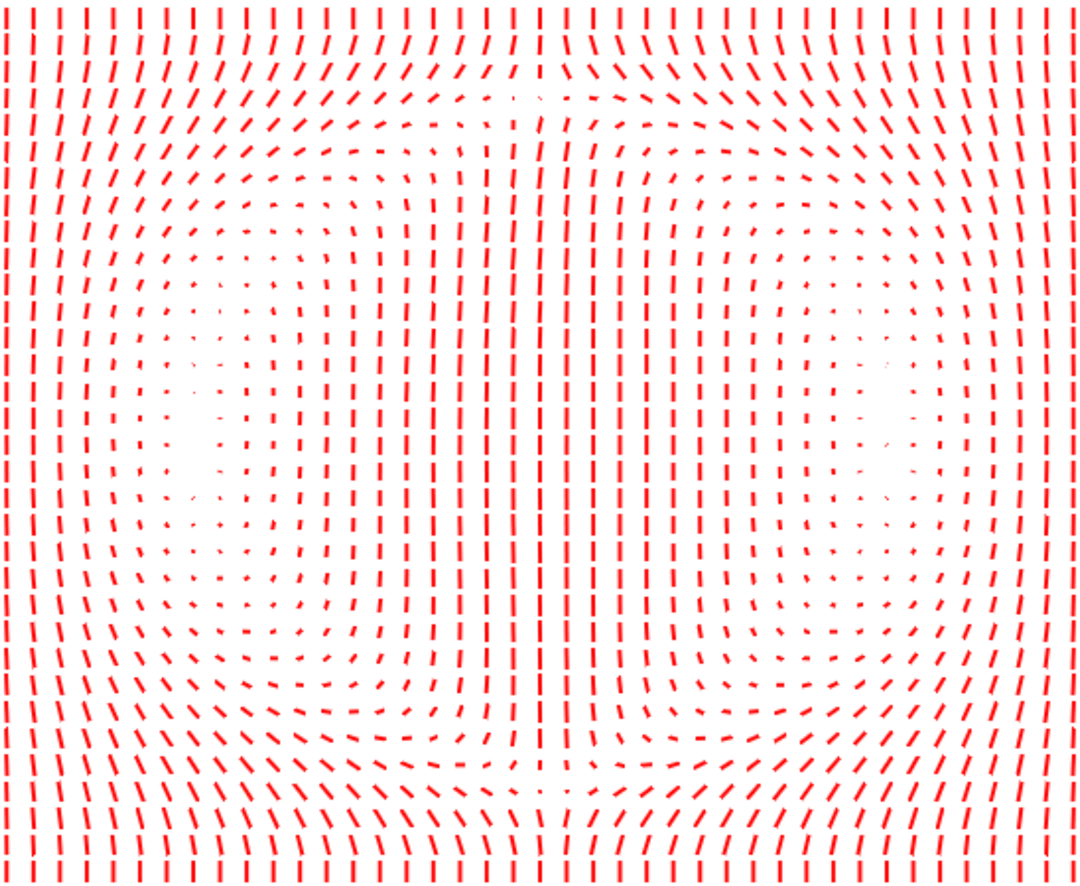


+ Nematic
x TIC
open square: CF1
filled square: CF2
Axially symmetric structures

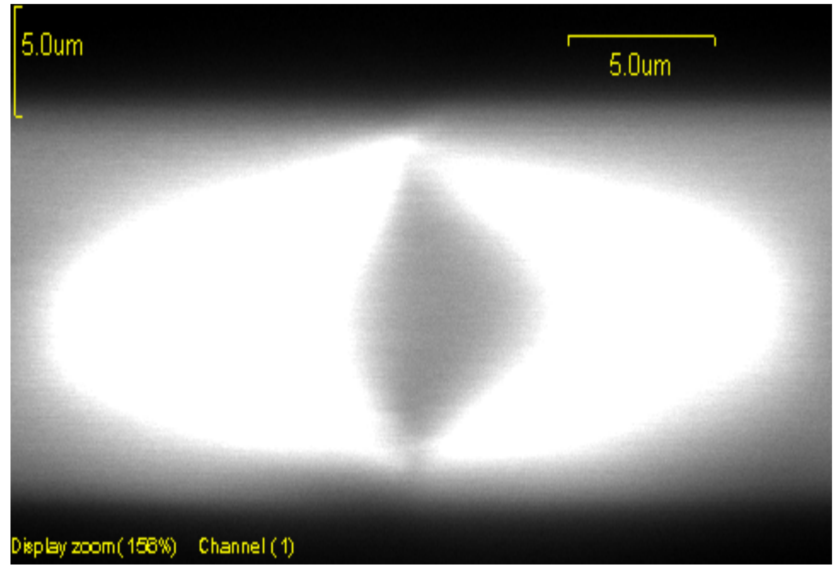
3D localized structure, $C = d / p = 1$



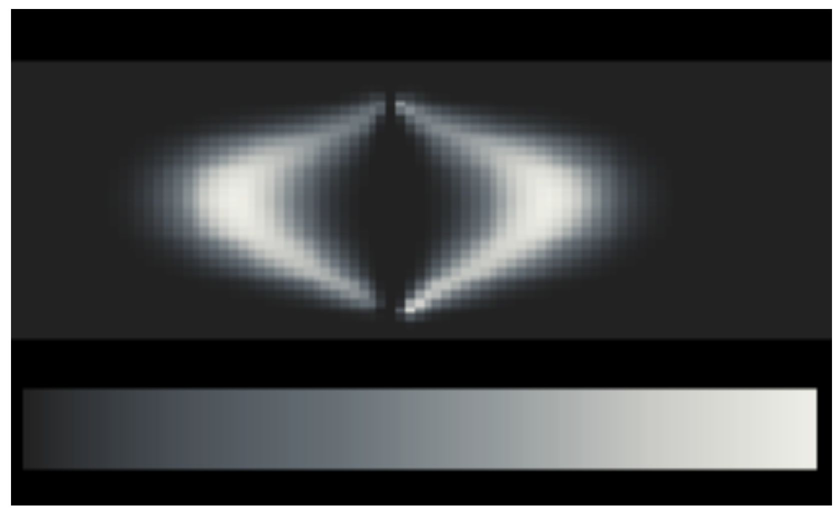
side view



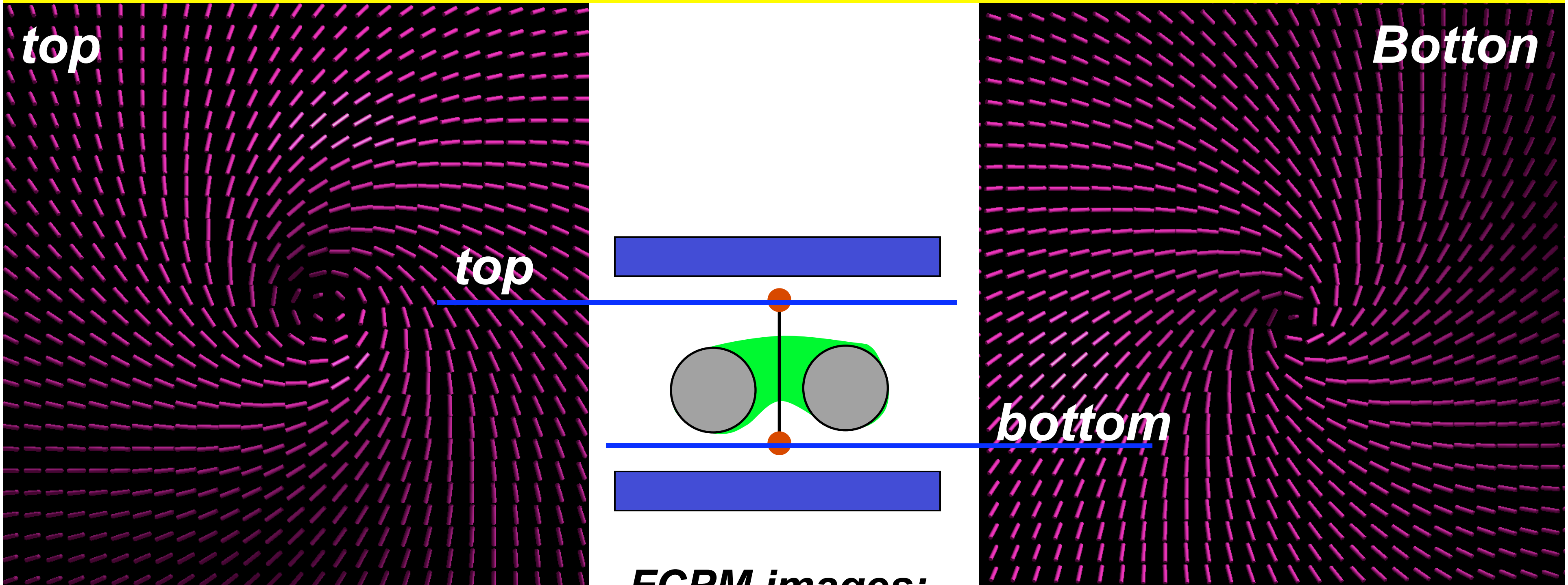
FCPM vertical cross-section



Computer-simullated

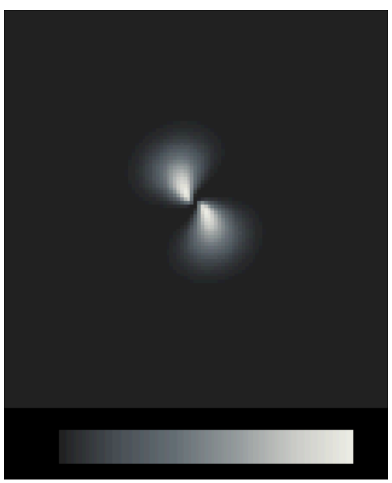


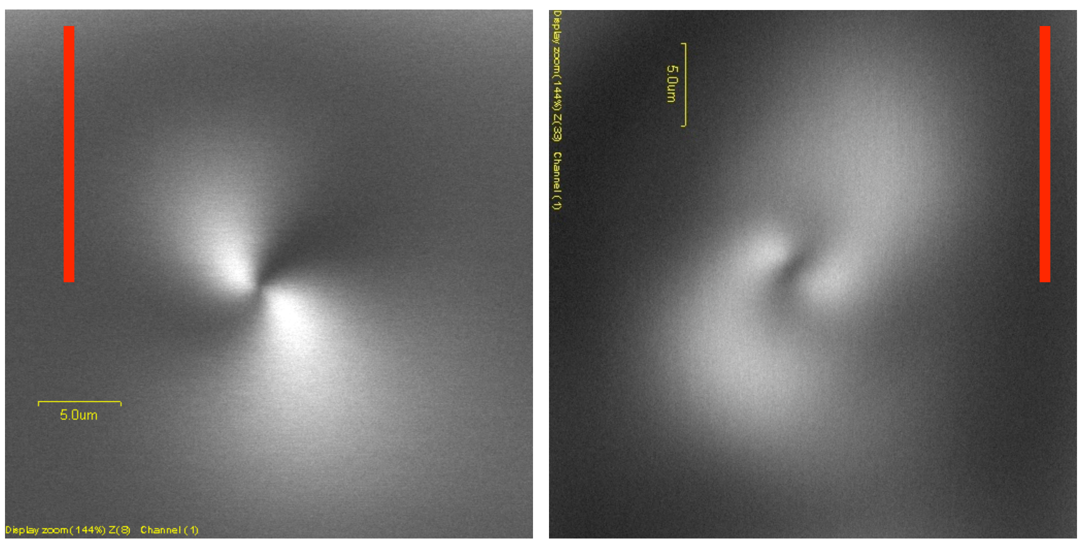
3D localized chiral LC structure, C = d / p = 1



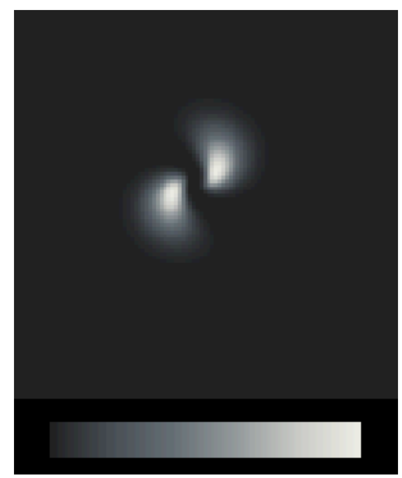
FCPM images:

Calculated:

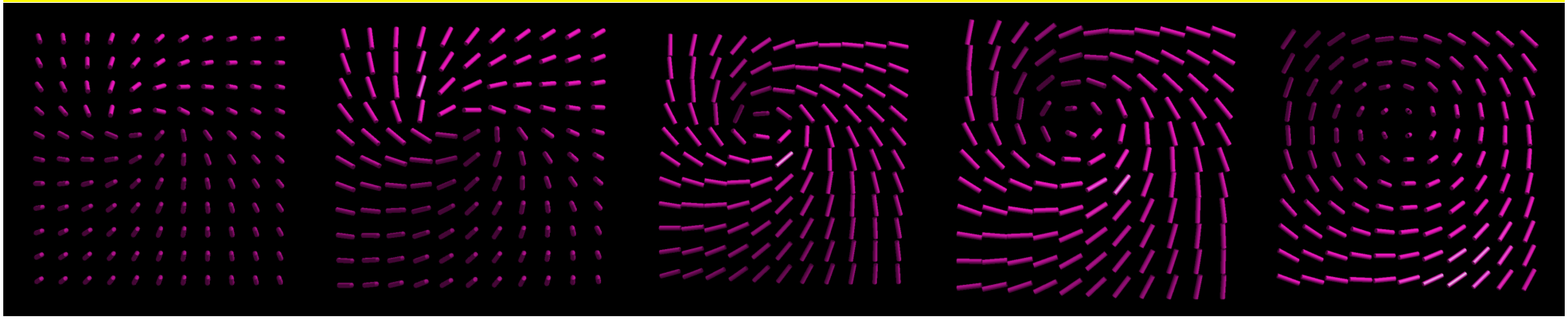


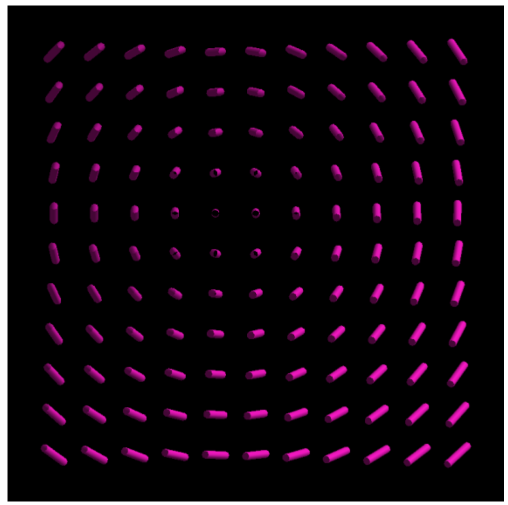


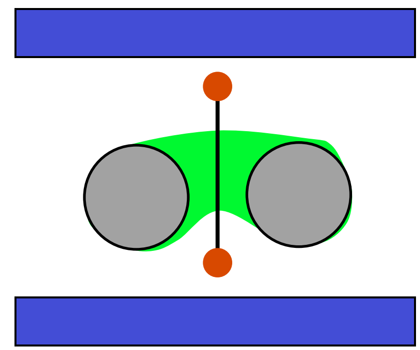
Calculated:

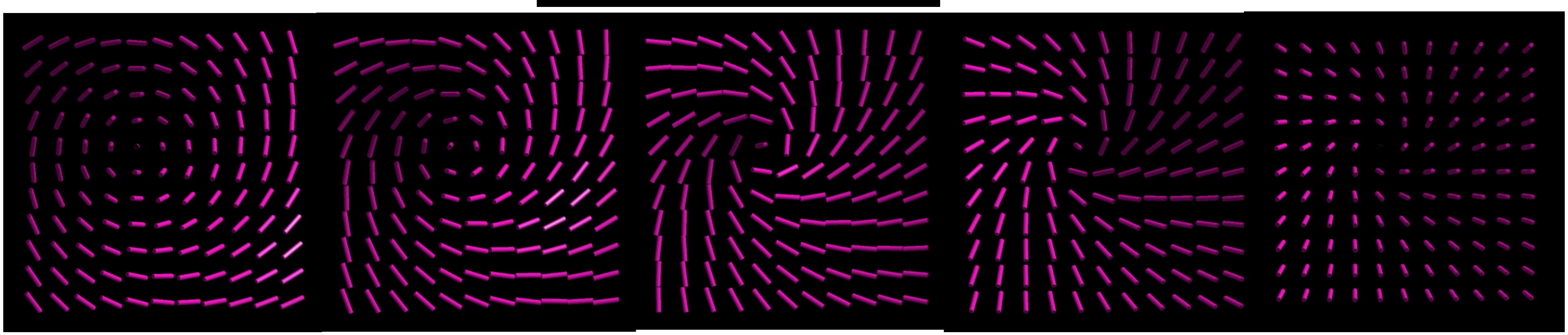


3D director structure: in-plane sections



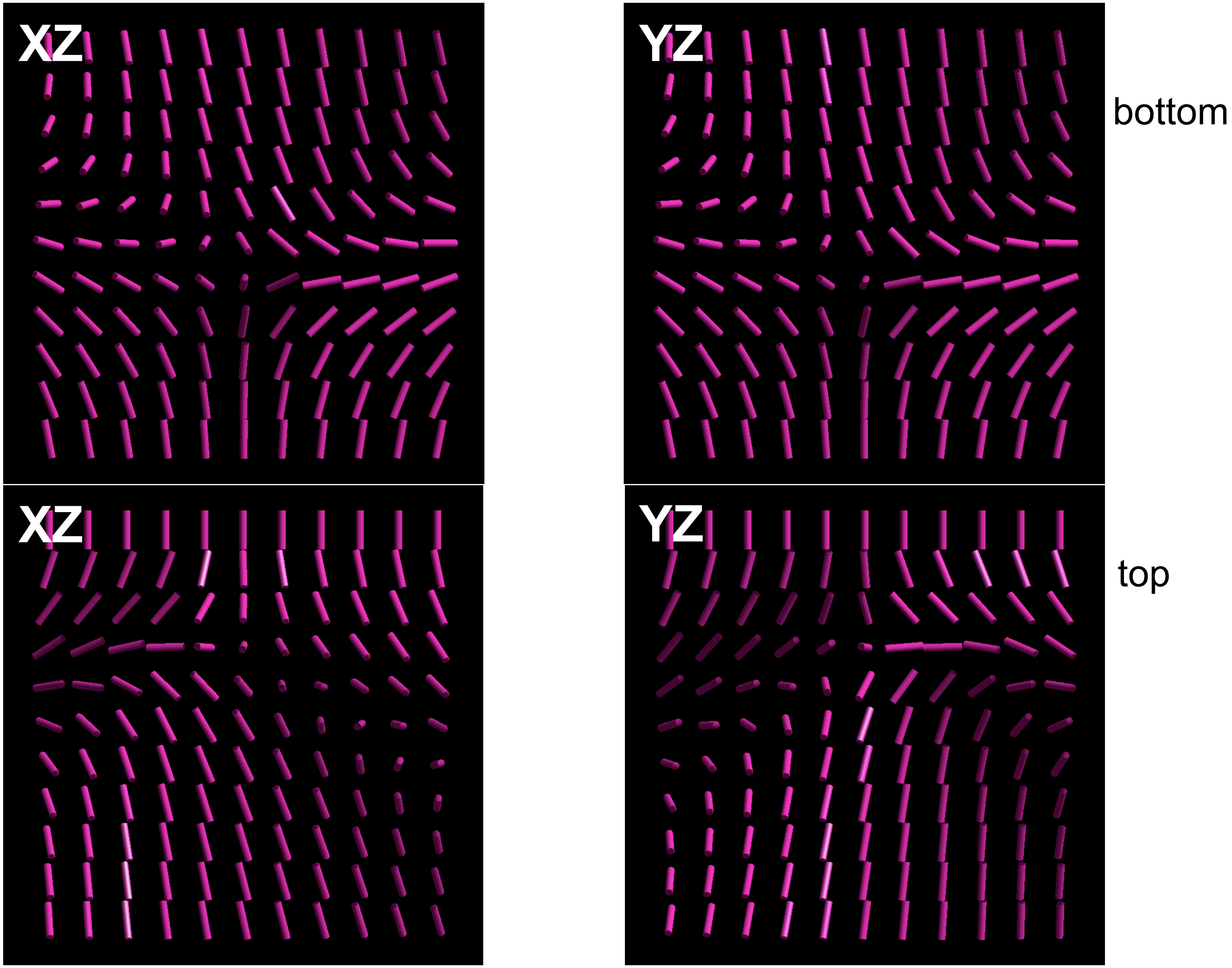




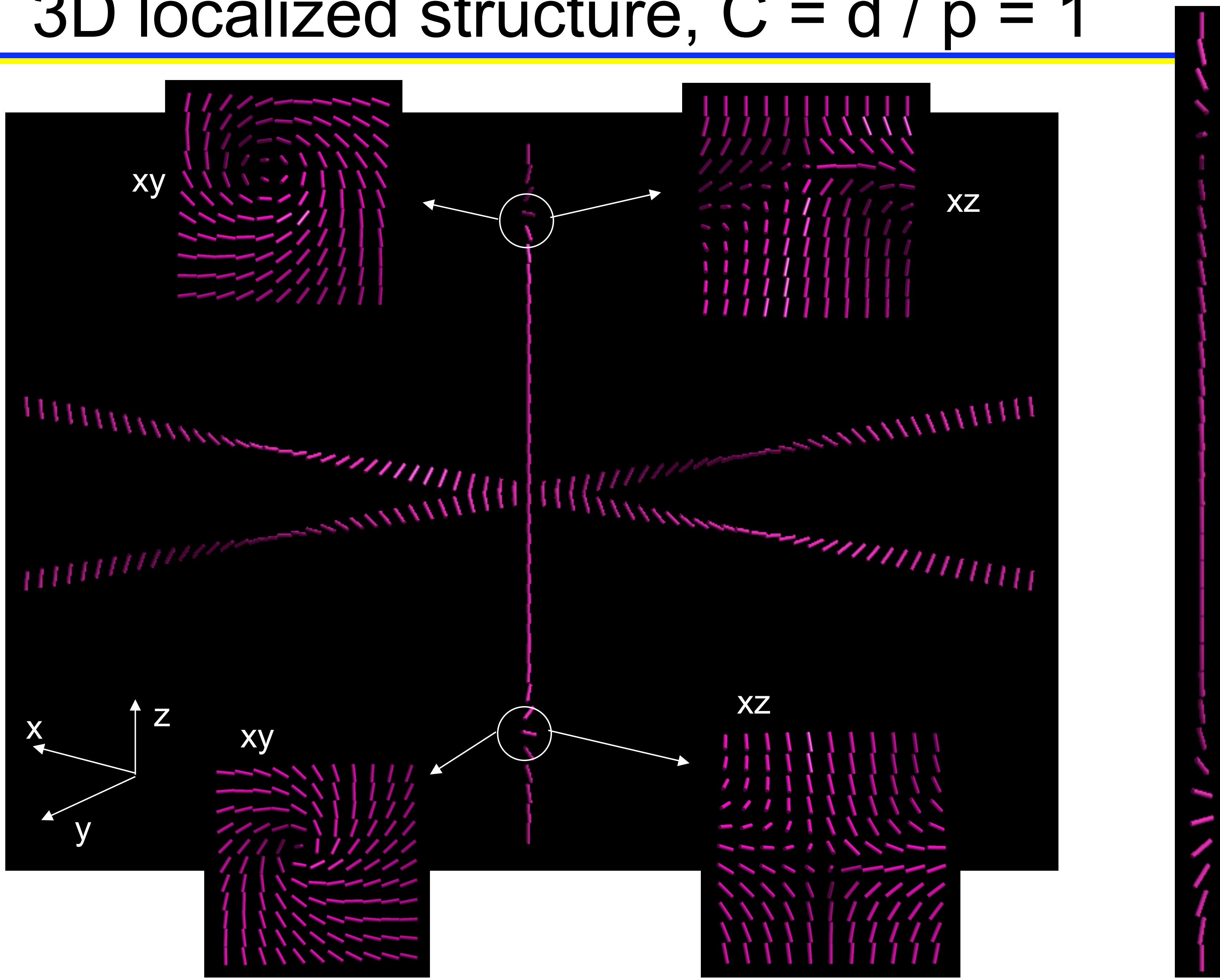


Point defects in the 3D localized structure

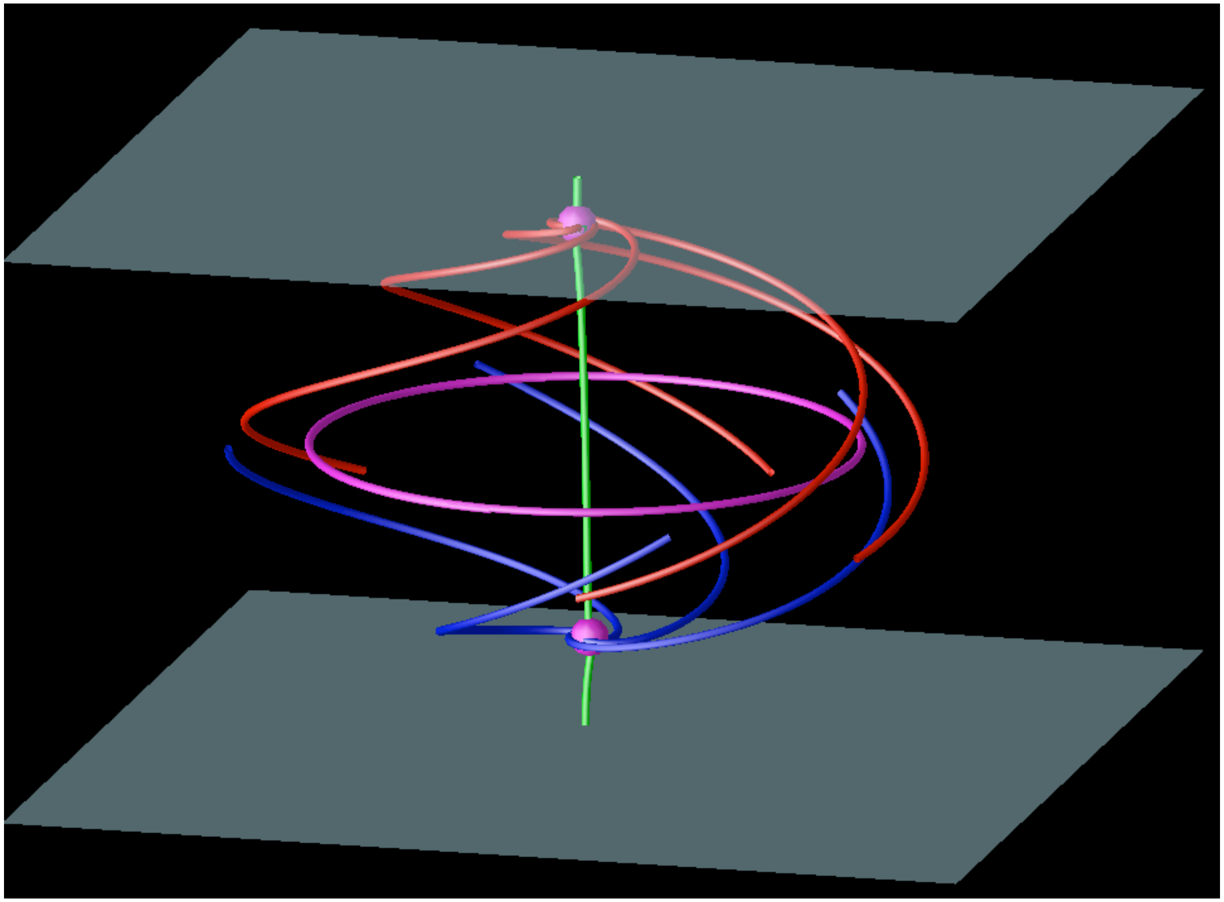
→ Hyperbolic point defects at two opposite surfaces;



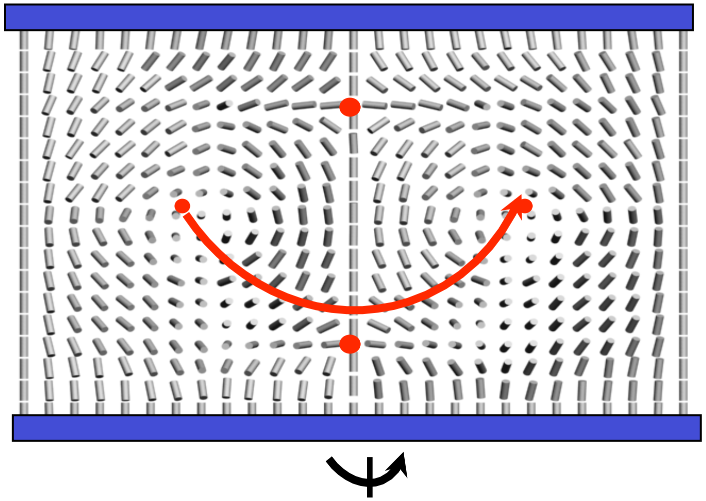
3D localized structure, C = d / p = 1



Topological skeleton of the director field **n**



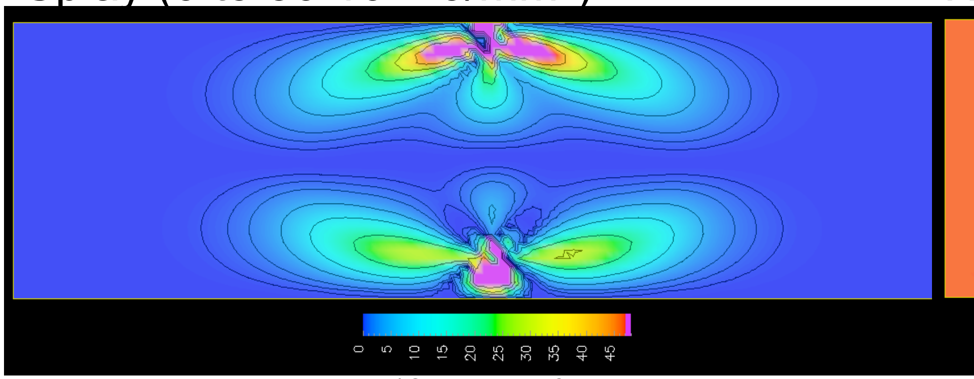
Matches experimental reconstruction:



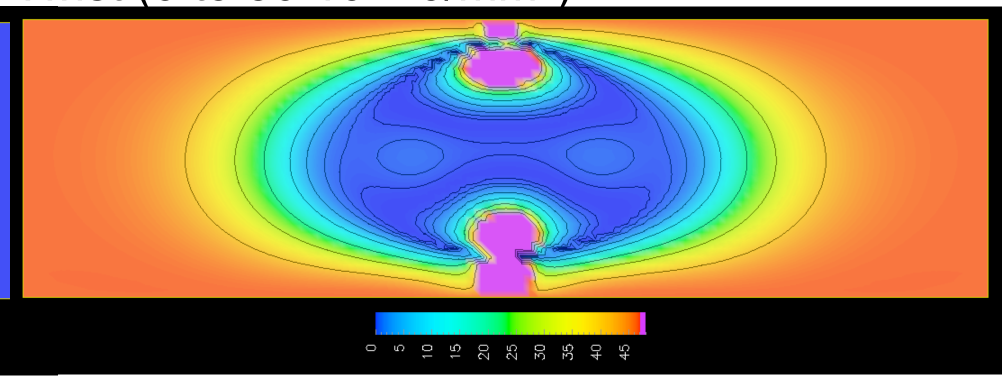
Total topological charge is conserved

Elastic Free Energy: topography of frustration

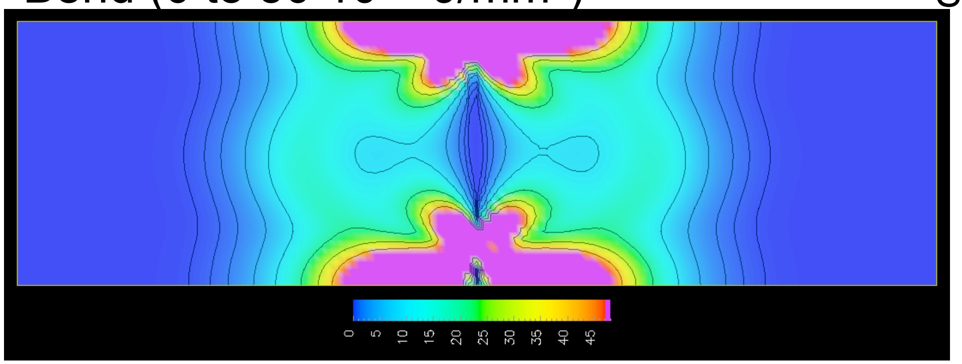
Splay (0 to 50 10^{-18} J/mm^3)



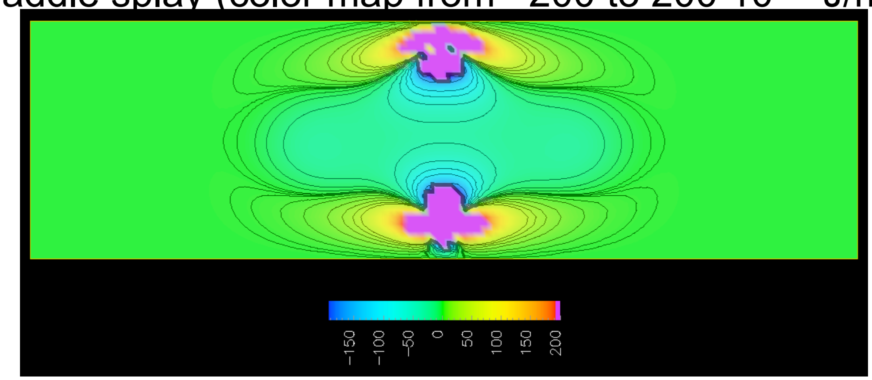
Twist (0 to 50 10^{-18} J/mm^3)



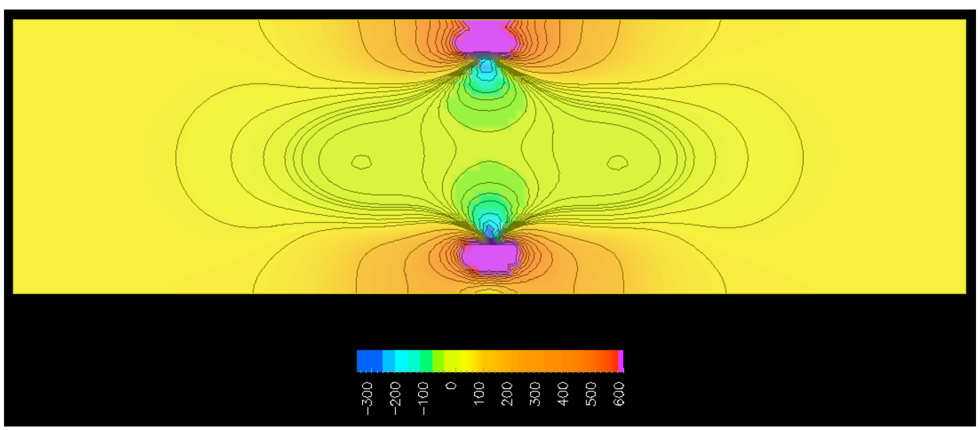
Bend (0 to 50 10^{-18} J/mm^3)



Saddle splay (color map from –200 to 200 10^{-18} J/mm^3)

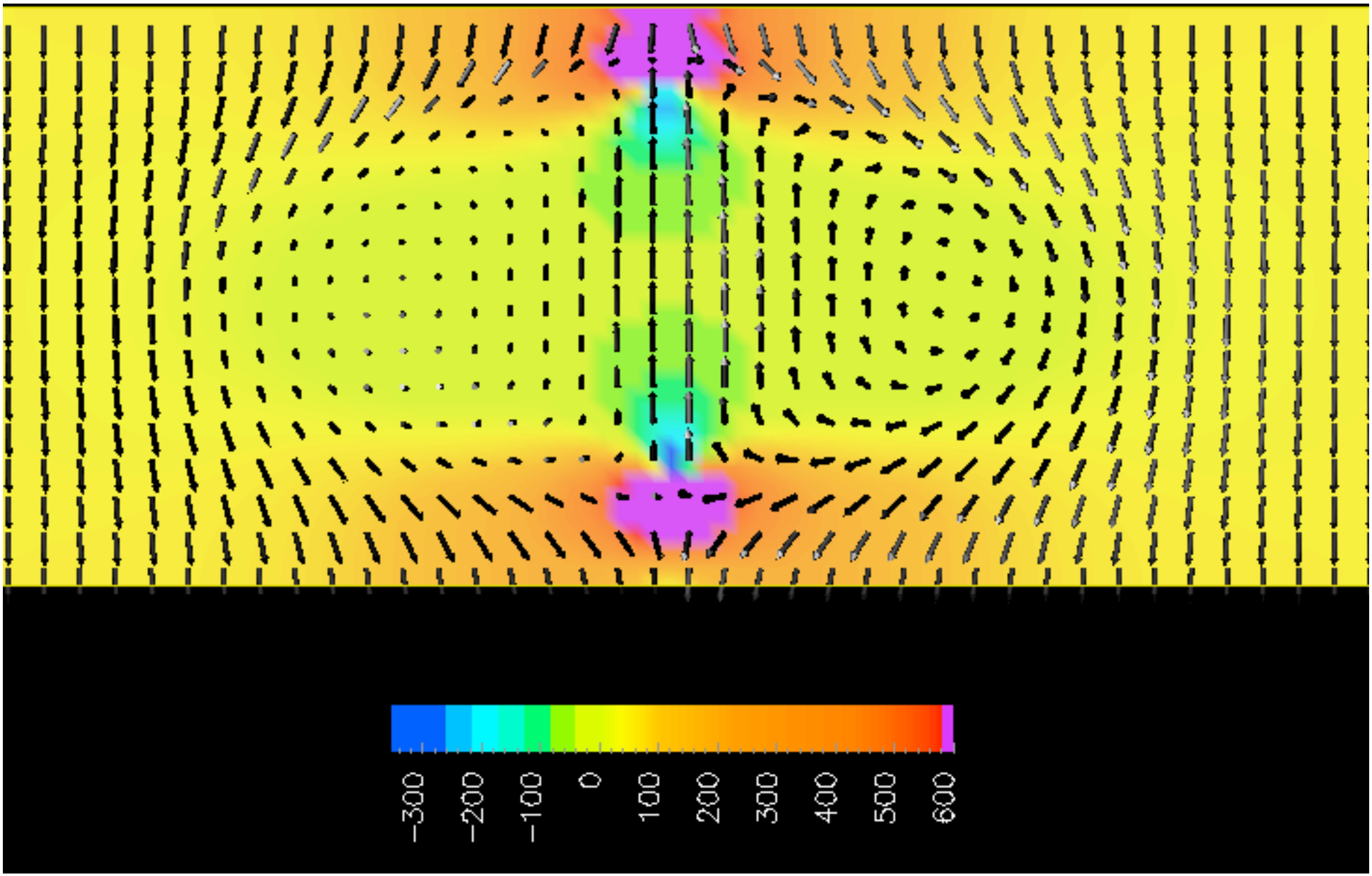


Total Elastic Free Energy (–300 to 600 10^{-18} J/μm^3)

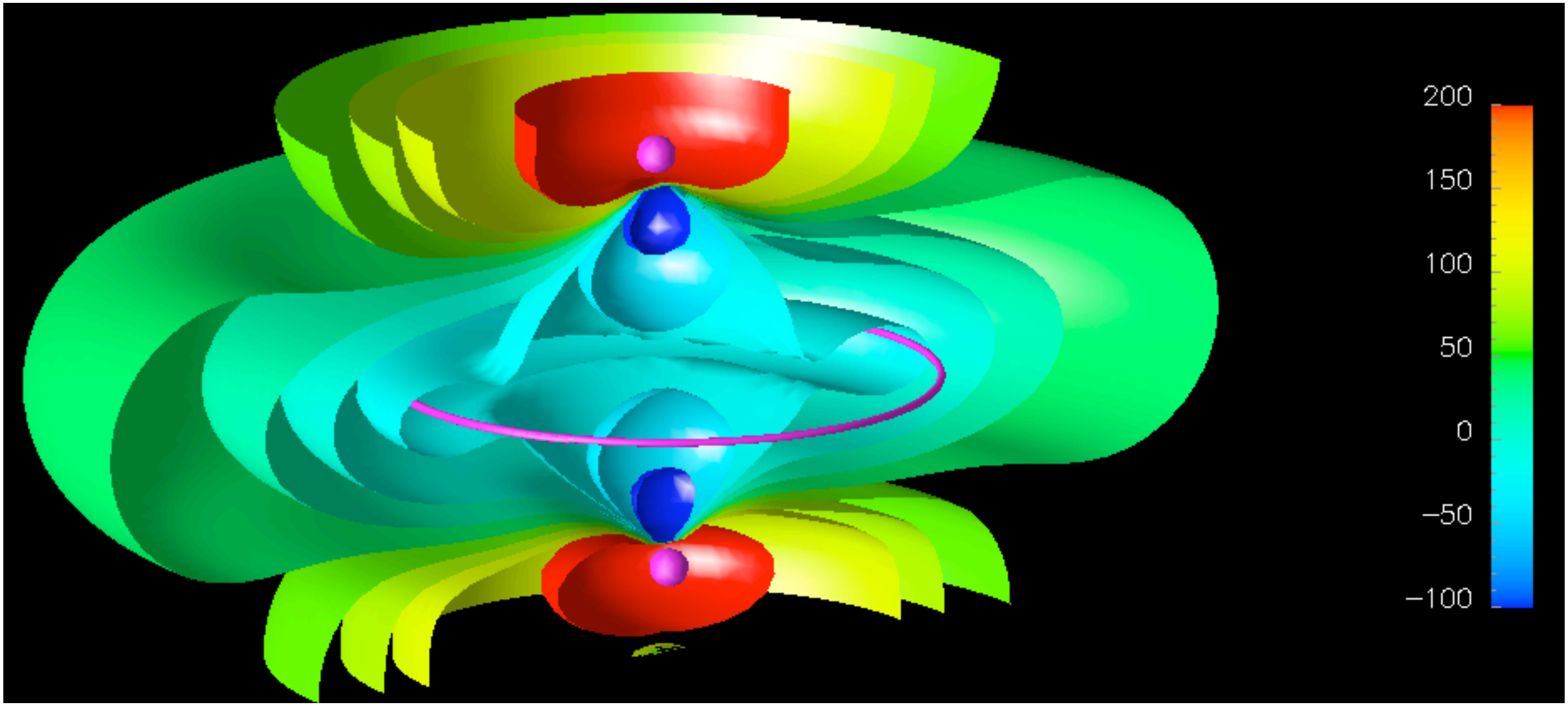


Different elastic energy terms are minimized in different parts of the structure

Total free energy density and director field



Total free energy density isosurfaces

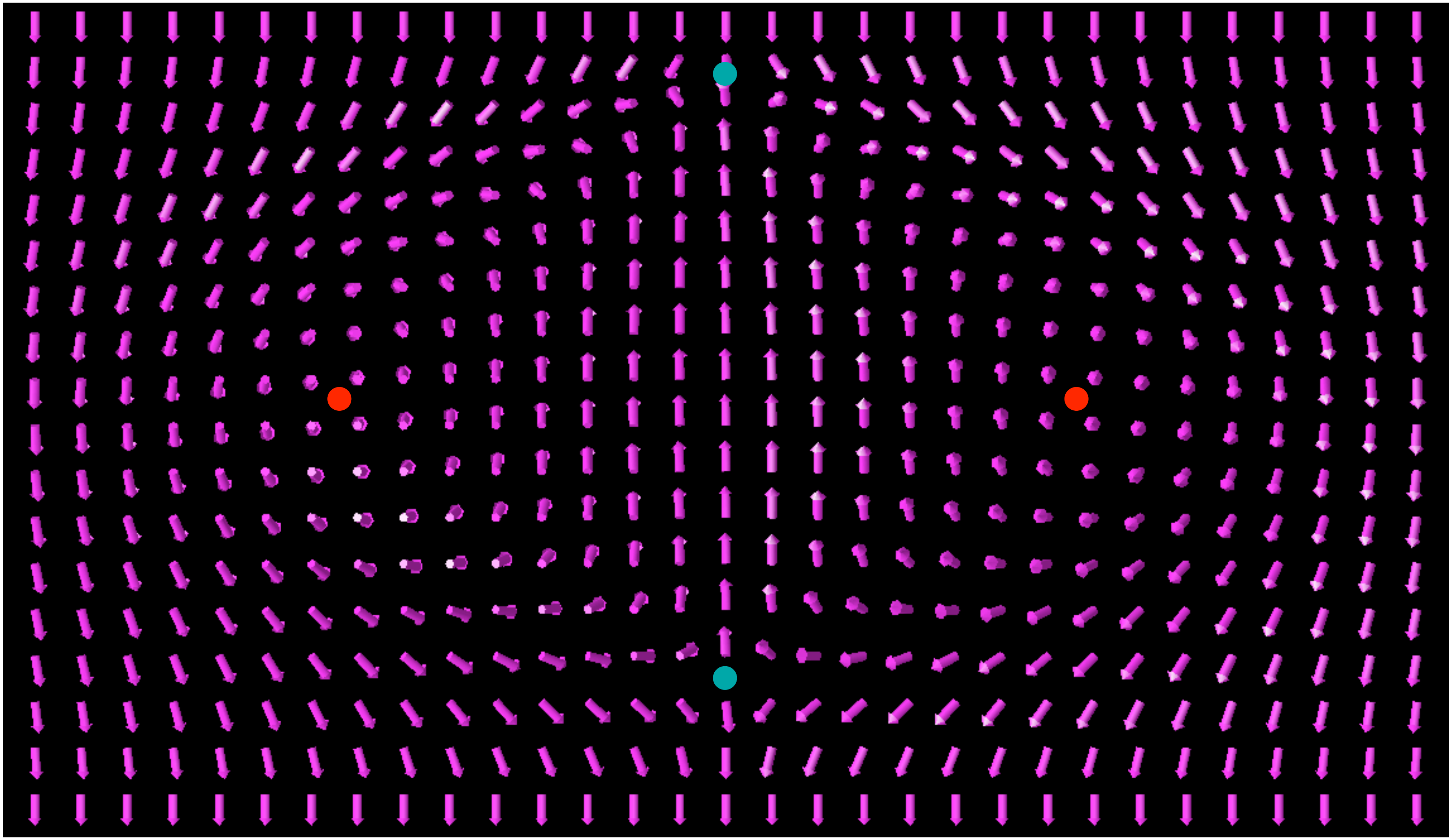


•The energy is minimized in the double-twisted part of the structure

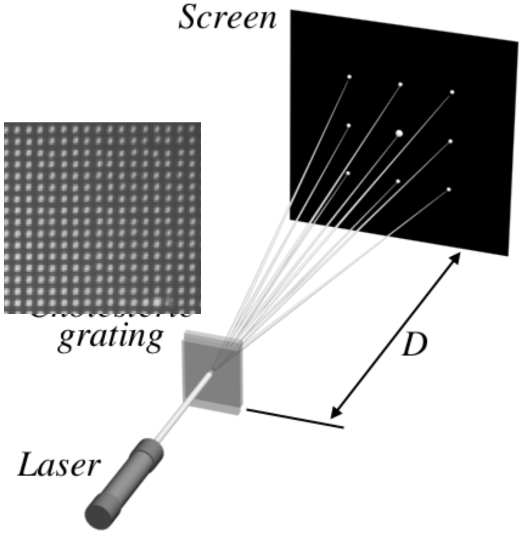
•Point defects – energetically-costly part of the structure;

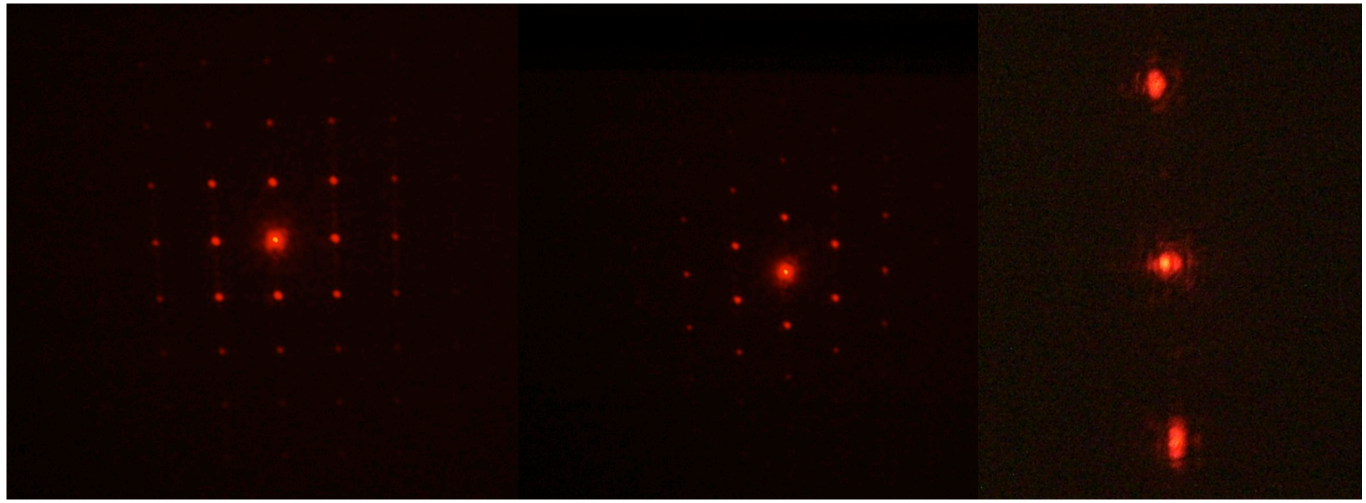
•Total free energy slightly lower than that of the unwound state;

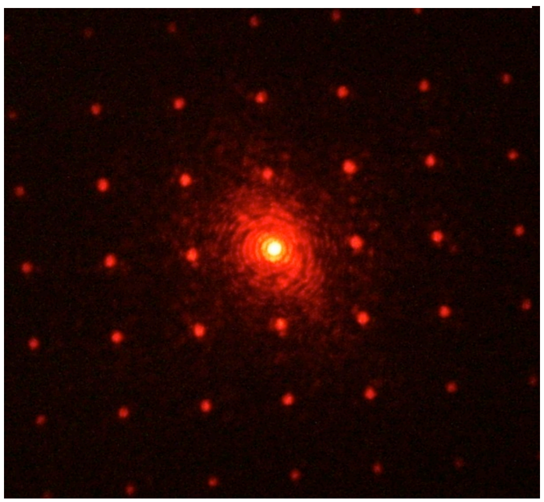
Can be realized in polar systems (chiral magnets, etc)

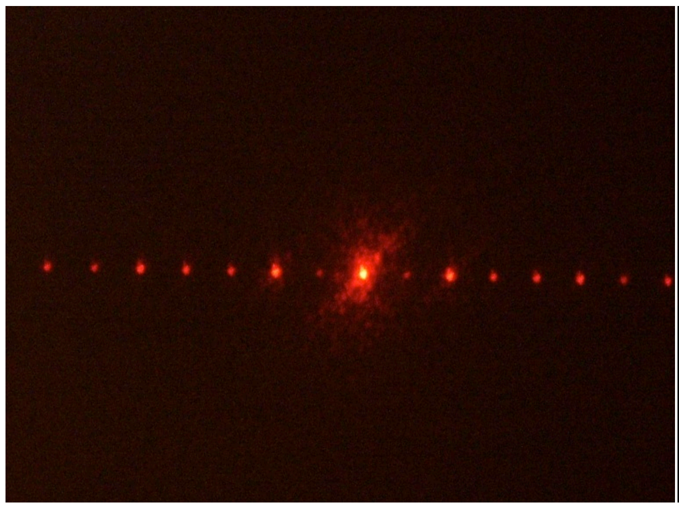


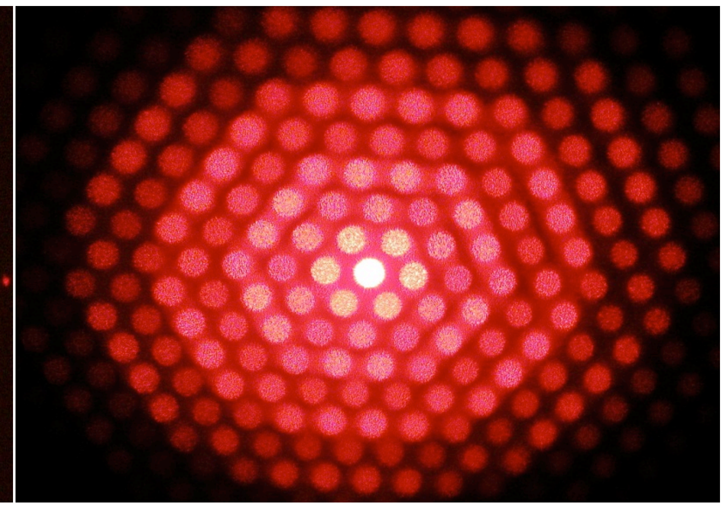
Optically-controlled tunable diffraction pattern





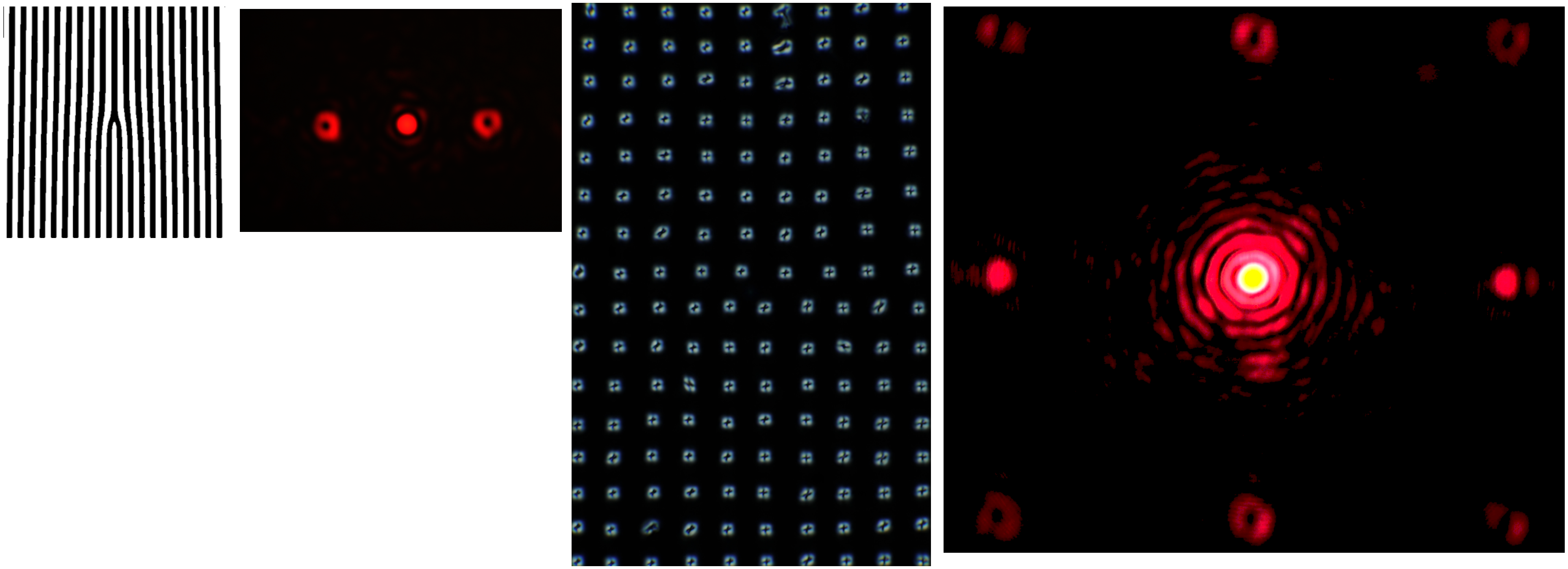




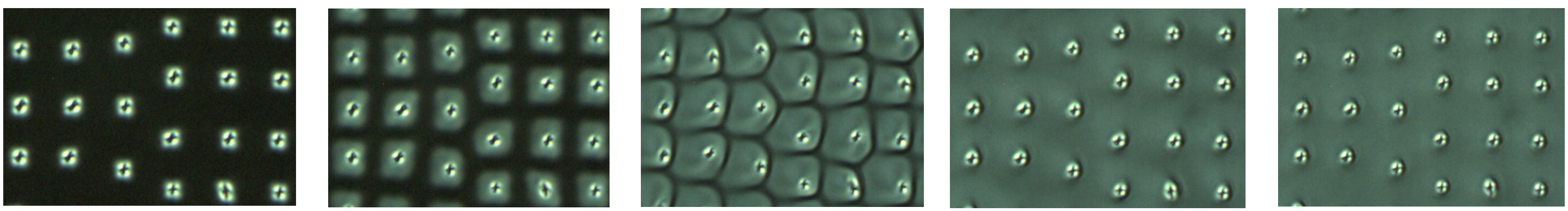


→Periodic structures generated by laser CW Nd: YAG λ=1064nm;
→Diffraction pattern obtained for HeNe Laser beam, λ=632.8nm

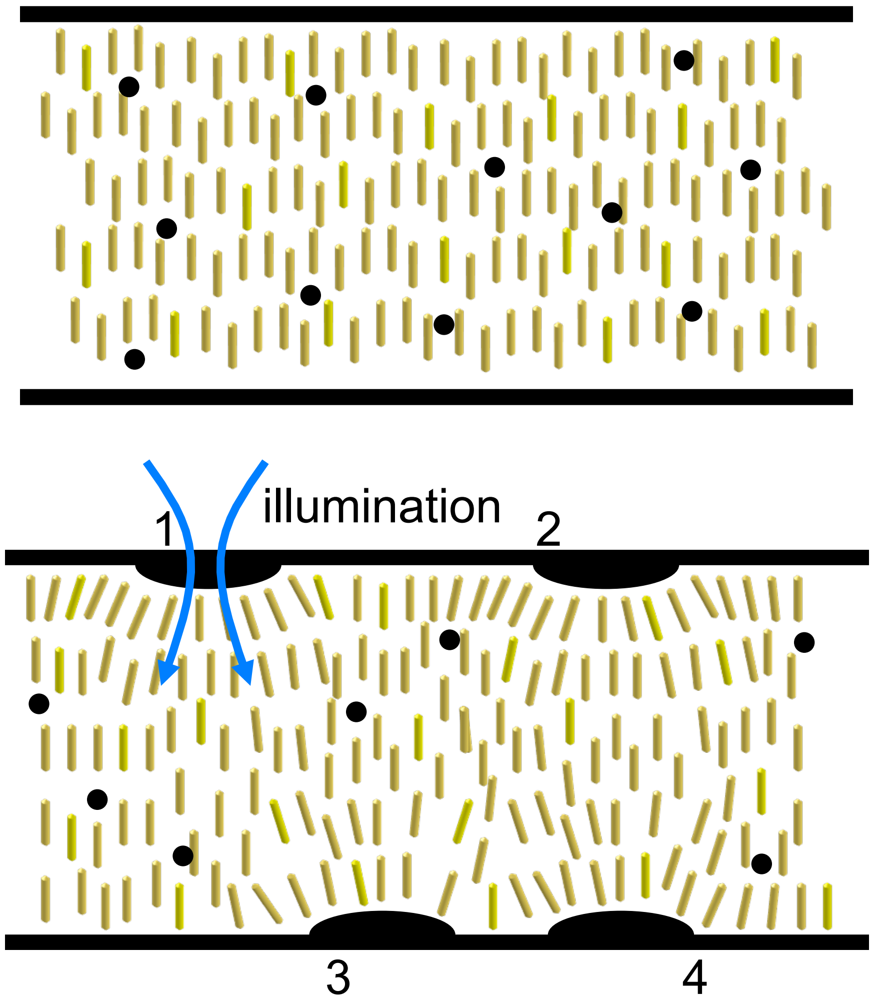
Generation & electric control of the Laguerre-Gaussian beams using torons

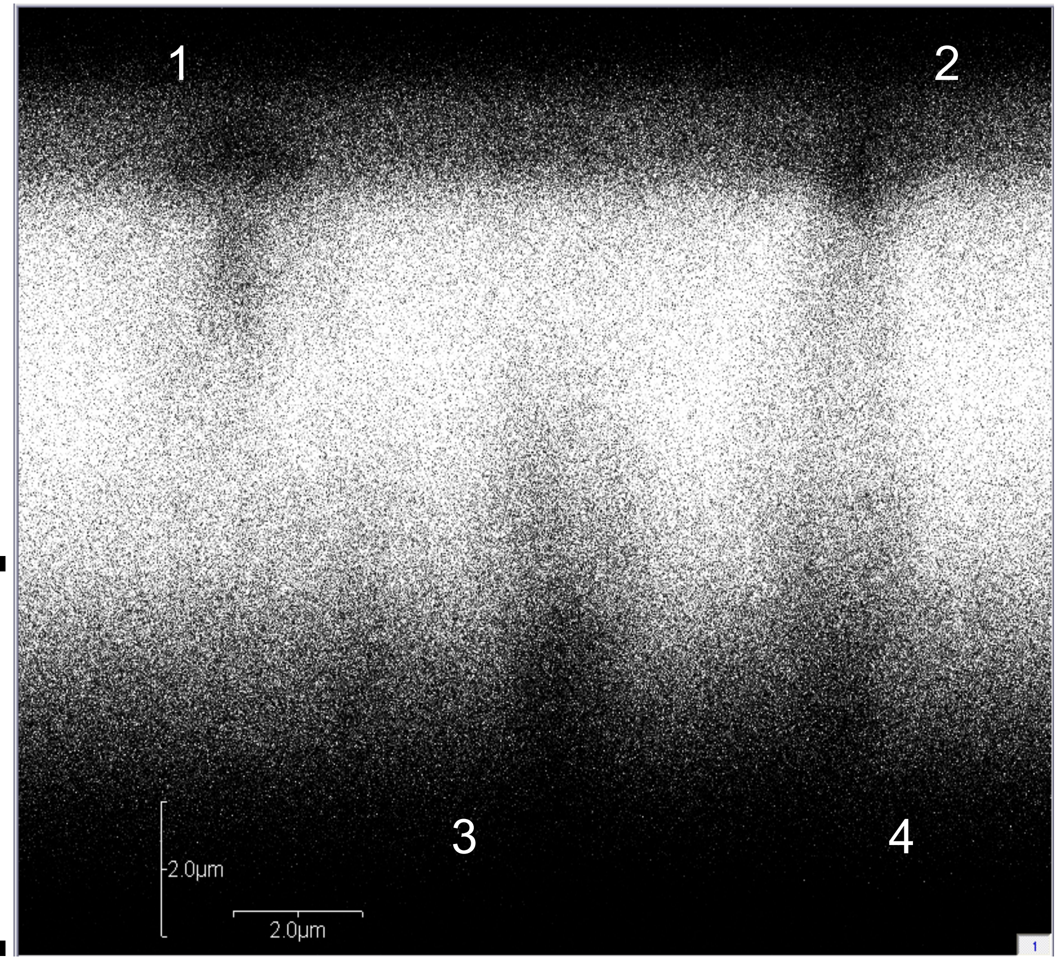


Gratings with a dislocation controlled by applying voltage:

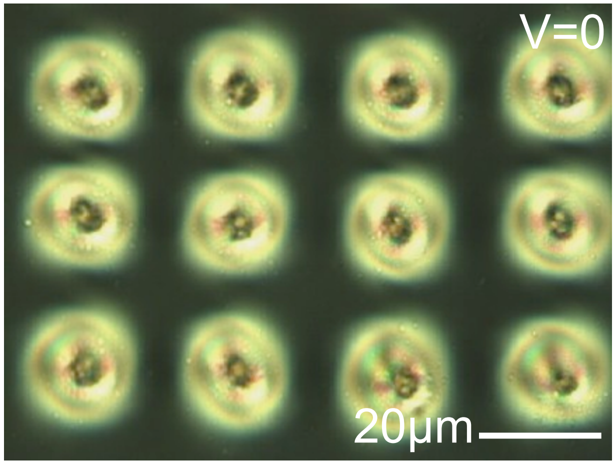


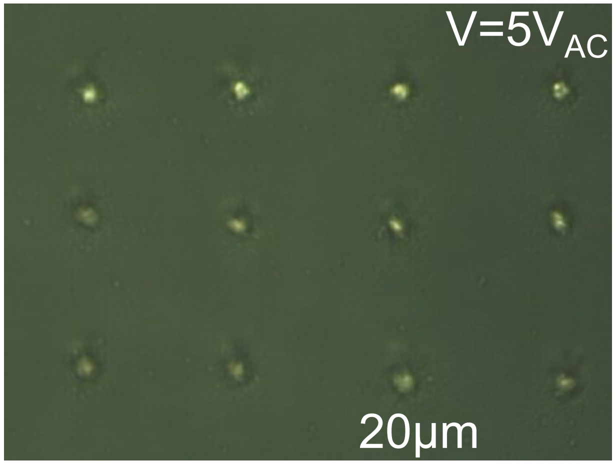
Creation of Torons by optical deposition of C_{60}

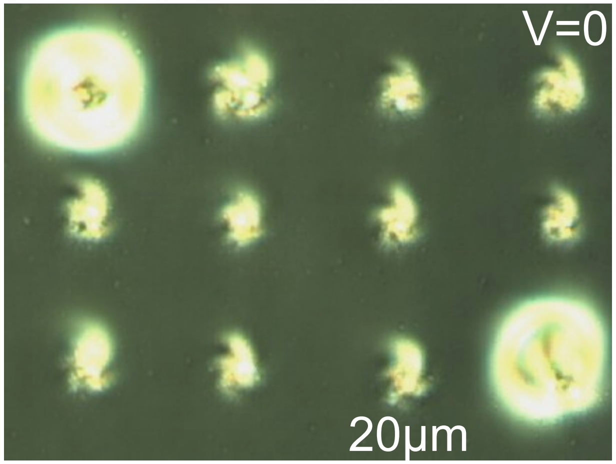


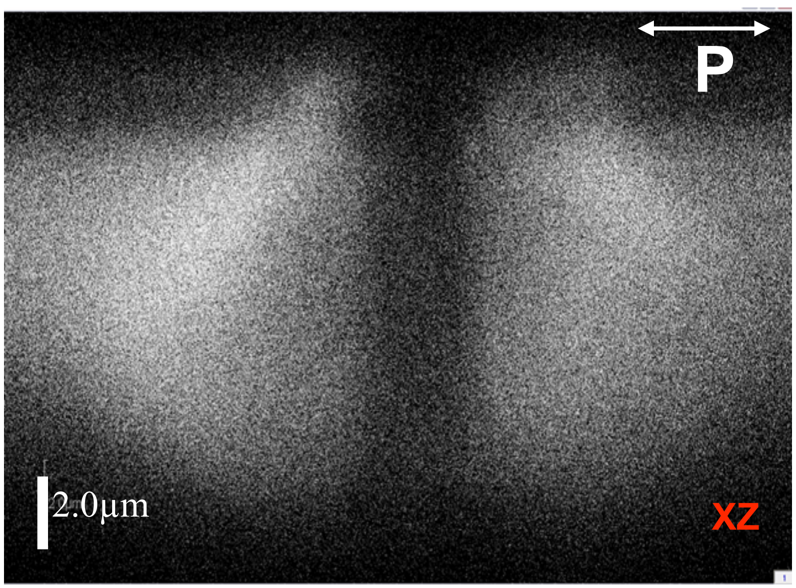


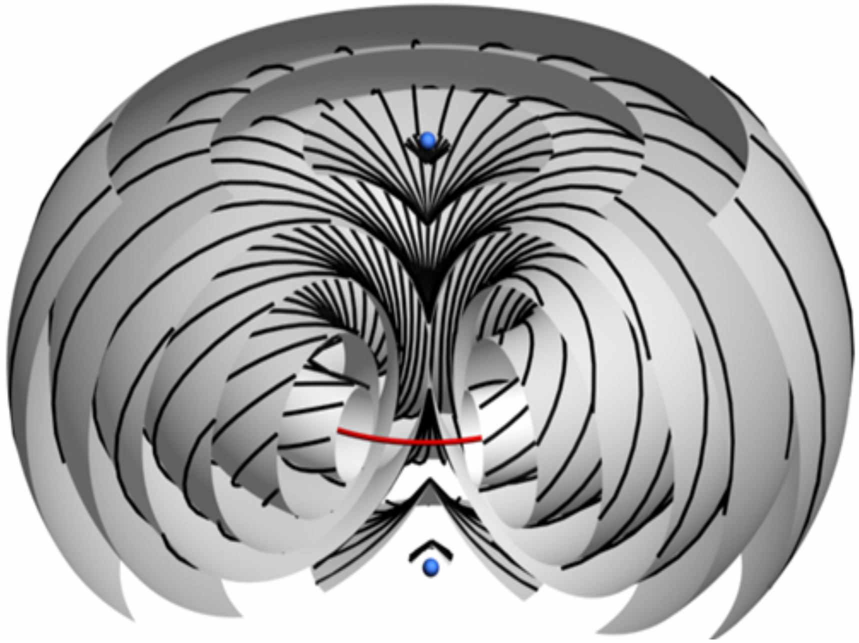
Optical & electric control





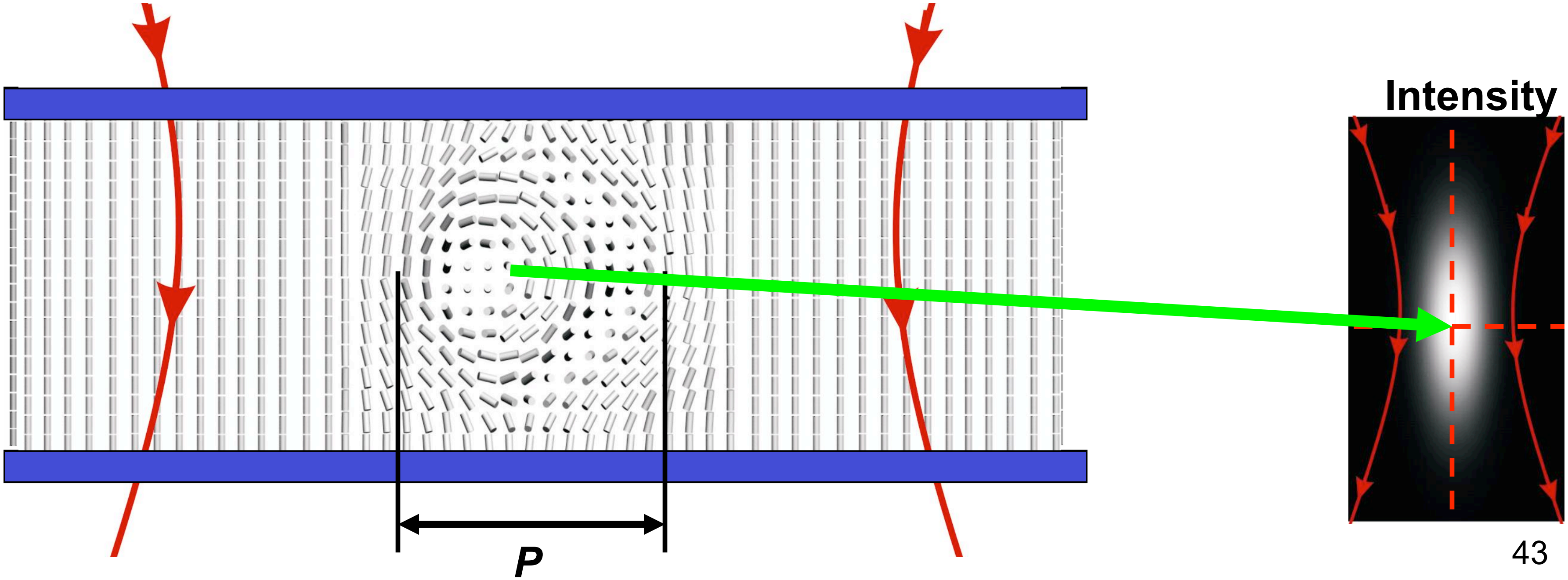






Size is not diffraction-limit constrained !!!

→Threshold effect;
→ Minimum periodicity/size is determined by LC's chirality (pitch p);
→ Can be tuned in the range 200nm-200μm using 1064nm IR laser;



Applications:

→Optically-generated tunable photonic crystals;
→All-optical diffraction gratings;
→optical data storage;
→All-optical information displays;

Conclusions & outlook

→ Laser-assisted control of multistable molecular orientation patterns and defects in LCs;

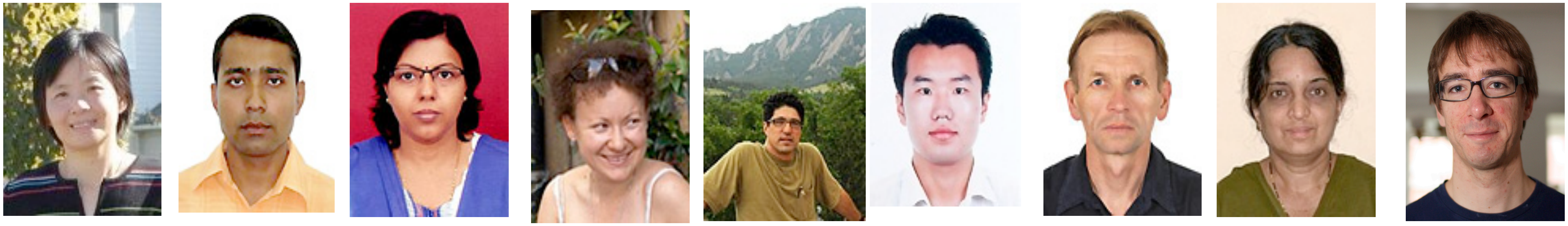
→ Ordered structures & defects directed & imaged by light

→ Light & optica vortices controlled by tunable ordered structures

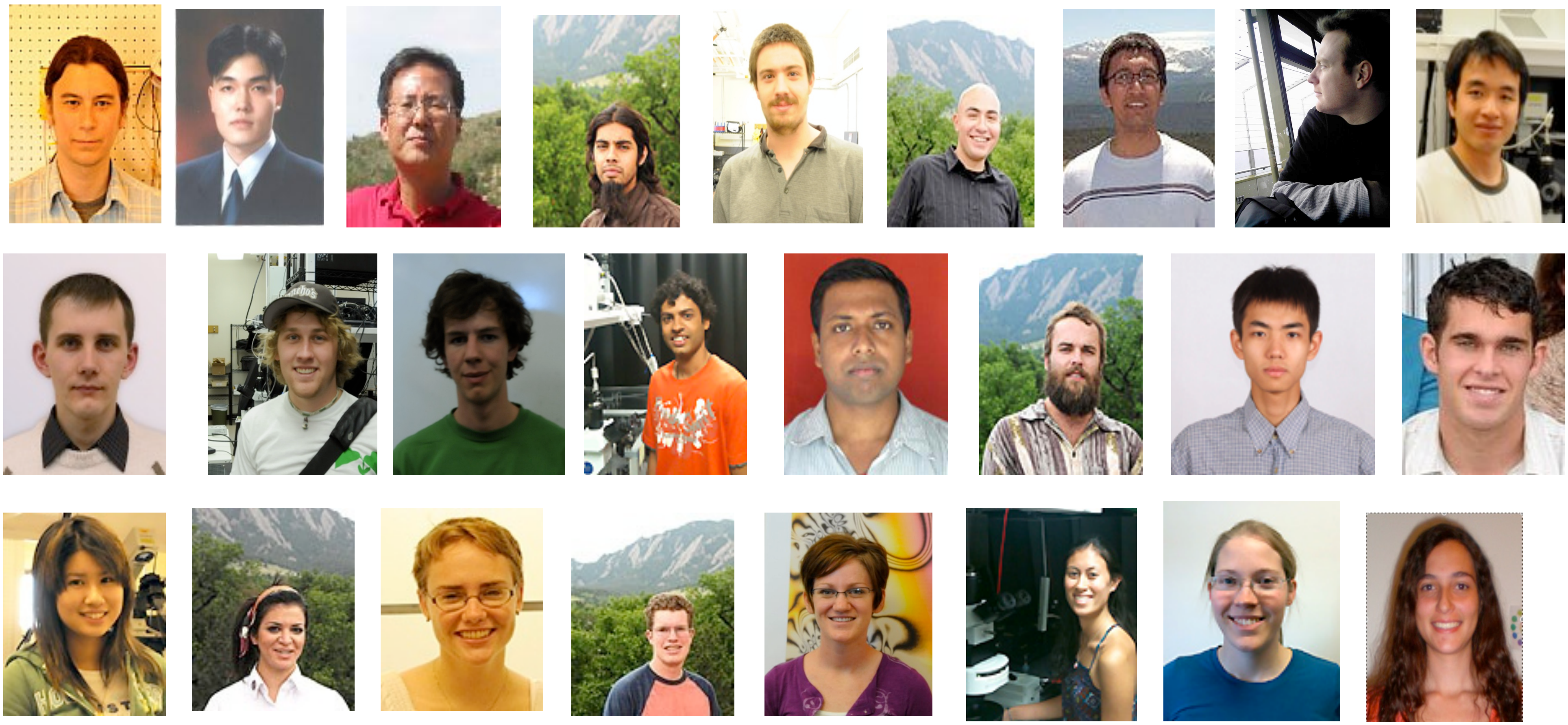
Thank you !!!

Our Team: http://www.colorado.edu/physics/SmalyukhLab

Visiting scientists



Postdocs and students



Remarks: recommended web tutorials

- http://plc.cwru.edu/tutorial/enhanced/main.htm
- http://dept.kent.edu/spie/liquidcrystals/
- http://dept.kent.edu/spie/
- http://www.personal.kent.edu/~mgu/ilcc/final%20layout/home.htm

Acknowledgements: