Guiding principles of light in frustrated chiral birefringent systems

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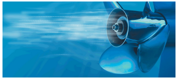
JAVNA AGENCIJA ZA RAZISKOVALNO DEJAVNOST REPUBLIKE SLOVENIJE

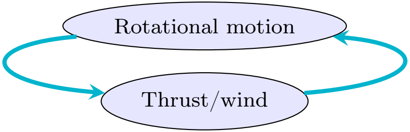
MARIE CURIE ACTIONS

Outline

Chirality in everyday life

- Chiral object: distinguishable from its mirror image.
- A common example: propeller.





- Without chirality, this conversion is not possible.

The cholesteric phase: a chiral anisotropic soft material

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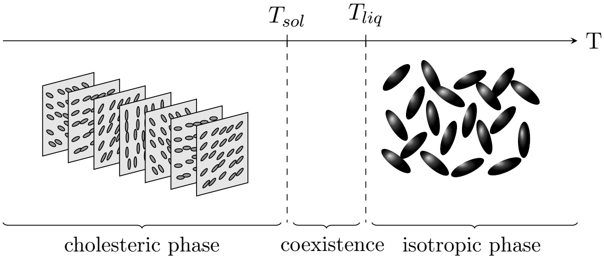
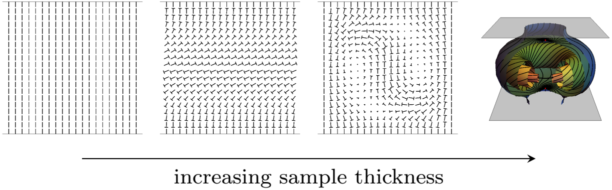


Frustration: confining cholesterics between two plates

- Surface constraint: molecules must be normal to the confining surface



P. J. Ackerman et al., *Scientific Reports* **2** (2012)

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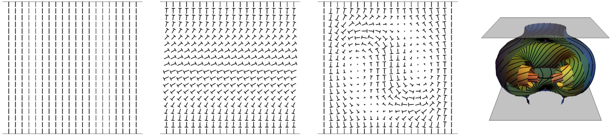
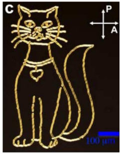
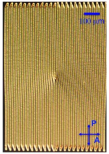
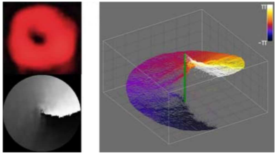


increasing sample thickness

- Arbitrary shapes can be written with thread-like structures!



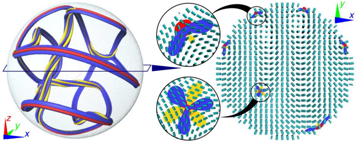




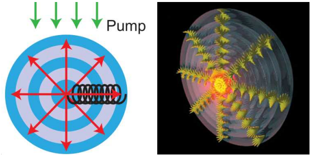
P. J. Ackerman et al., *Scientific Reports* **2** (2012)

Frustration: confining cholesterics inside droplets

Topological zoo of free standing knots



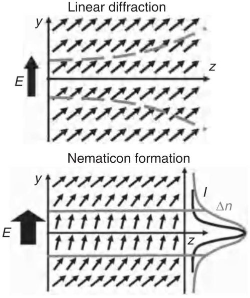
Lasing in a cholesteric droplet: an omnidirectional microscopic coherent light source

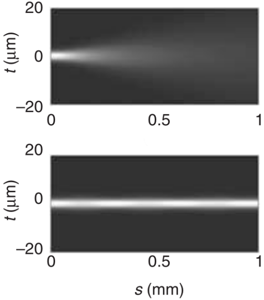


D. Seč, S. Čopar and S. Žumer, *Nature communications* **5** (2014)
M. Humar, *Liquid Crystals* **43** (2016)

Problematics

Non-linear optical response of liquid crystal systems:





Increasing beam power

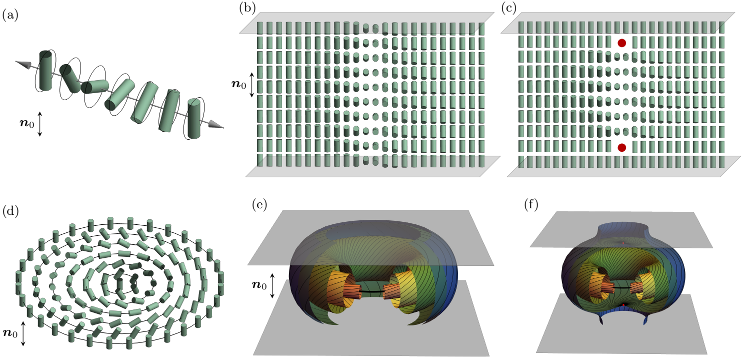
G. Assanto. *Nematicons.* John Wiley & Sons, 2013

Problematic 1

Role of chirality in the non-linear optical response of a frustrated cholesteric?

Problematics

Two classes of soft chiral topological solitons in frustrated cholesterics



translational invariance

rotational invariance

Problematic 2

Localized and robust chiral birefringent structures ⇒ interesting interaction with light?

Outline

Motivations

- Recent advances in LC-based light application: tunable microresonators, micro-optical elements, diffraction gratings...

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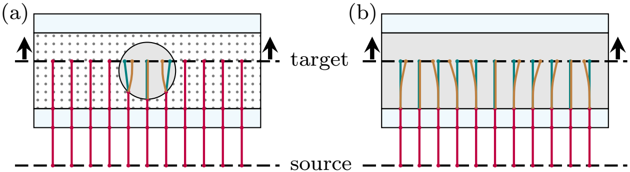
Need for advanced light propagation code, if possible open-source

First approach: Hamiltonian ray-tracing and energy transport

$$\frac{\mathrm{d}\eta}{\mathrm{d}\bar{s}} = \{\boldsymbol{\eta}, \mathcal{H}\}$$

$$\boldsymbol{\eta} \equiv (\boldsymbol{x}, \boldsymbol{p})$$



G. Poy and S. Žumer, *Soft Matter* **15** (2019)

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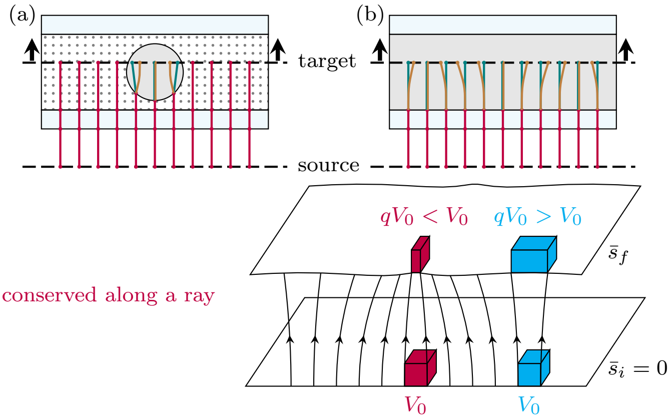

$\mathcal{F}^{(\alpha)} = n_{\mathrm{eff}}\,\sqrt{q}\,E$ conserved along a ray

Advantage: intuitive physical interpretation

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Second approach: physics-based splitting of the wave equation

- Wave-equation in anisotropic media: $\left[\partial_k\partial_k\delta_{ij} - \partial_i\partial_j + k_0^2\epsilon_{ij}\right] E_j = 0$

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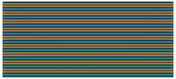
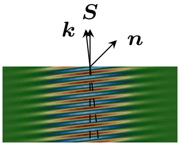
- What's inside $\boldsymbol{\mathcal{P}}$?



Phase op. $\boldsymbol{K} \sim k_0^2 \boldsymbol{\epsilon}$



Walkoff op. $\boldsymbol{W} \sim (\boldsymbol{\epsilon}\, \boldsymbol{u}_z) \otimes \boldsymbol{\nabla}_\perp$

Diffraction op. $\boldsymbol{D} \sim \boldsymbol{\Delta}_\perp$

Advantage: fast and accurate simulations

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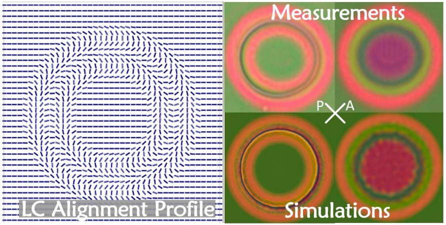
Nemaktis: an open-source package for polarised microscopy

- The open-source package includes:
  - Low-level simulation backends (C++, python)
  - An easy-to-use high-level interface (python)
  - A graphical interface for micrographs simulation



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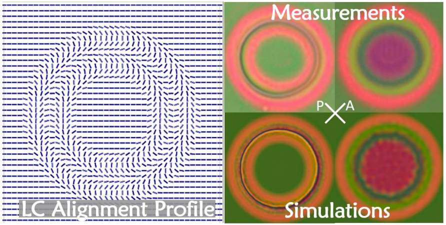

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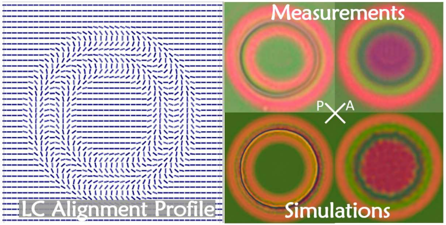

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- Closed-source BPM code for advanced uses: wide-angle beam deflection, non-linear optics, etc.

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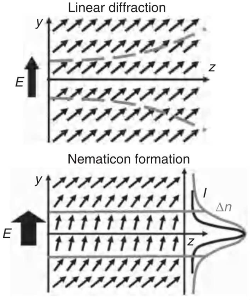
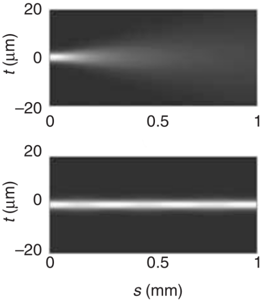
Outline

Motivations

Spatial light solitons in liquid crystals: nematicons





Increasing beam power

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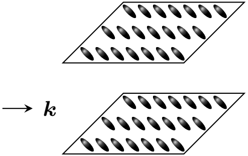
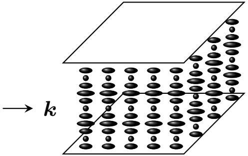
Motivations

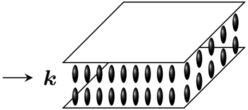
Studied systems in the past 20 years:



thick samples with planar $\boldsymbol{n}$



thick samples with cholesteric helix



thin samples with homeotropic $\boldsymbol{n}$

What about confined chiral systems? Can we amplify the optical response with chirality?

Orientational elasticity and non-linear interactions

Free energy of the liquid crystal phase:

$$F[\boldsymbol{n},\boldsymbol{E}] = \int_V \mathrm{d}V \left[f_\mathrm{F}(\boldsymbol{n},\nabla\boldsymbol{n}) - \frac{\epsilon_0\epsilon_a \left|\boldsymbol{n}\cdot\boldsymbol{E}\right|^2}{4} \right]$$

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Non-linear iterative scheme:

- $\boldsymbol{E}_{k+1}$: BPM solution with $\boldsymbol{\epsilon} = \epsilon_\perp \mathbf{I} + \epsilon_a \boldsymbol{n}_k \otimes \boldsymbol{n}_k$
- $\boldsymbol{n}_{k+1} = \boldsymbol{n}_k + \mu \frac{\delta F}{\delta \boldsymbol{n}} \left[\boldsymbol{n}_k, \boldsymbol{E}_{k+1} \right]$

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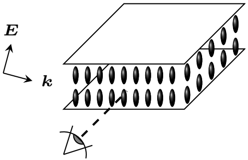
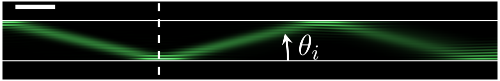
Typical running time for a mesh of 3×10^6 points: **4 s / step**
(Full resolution of Maxwell equations for the same mesh: **$\sim$ 1 h**)

Side-view observations

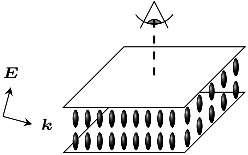


Side slice of beam intensity (simulation):



Side slice of 3PF signal (experiment):

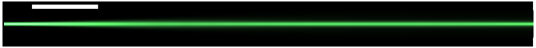
Top-view observations



Top view of the thickness-averaged laser intensity (simulation):

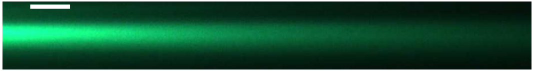
Linear optical regime

Non-linear optical regime

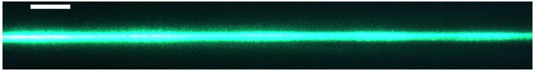


Top view of the scattered laser light (experiments):

Linear optical regime

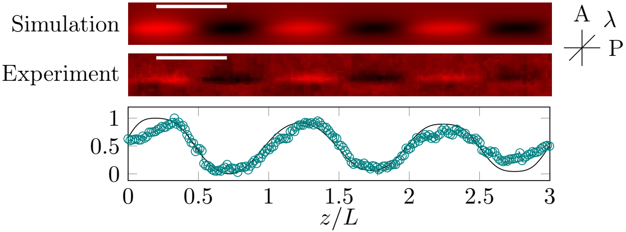


Non-linear optical regime

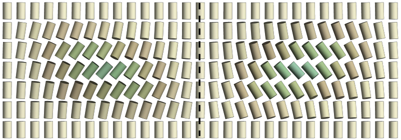


Top-view observations

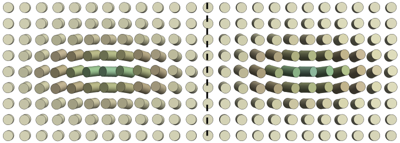
Top view polarised optical micrograph:



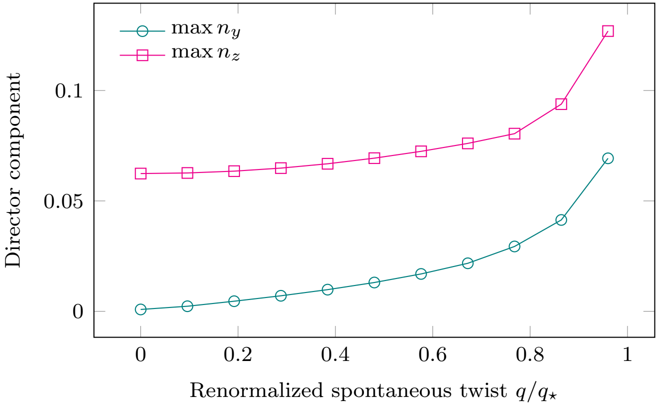
Side slice of director field



Mid-sample slice of director field



Chirality-enhanced non-linear optical response



G. Poy *et al.*, *Physical Review Letters* **125** (2020)

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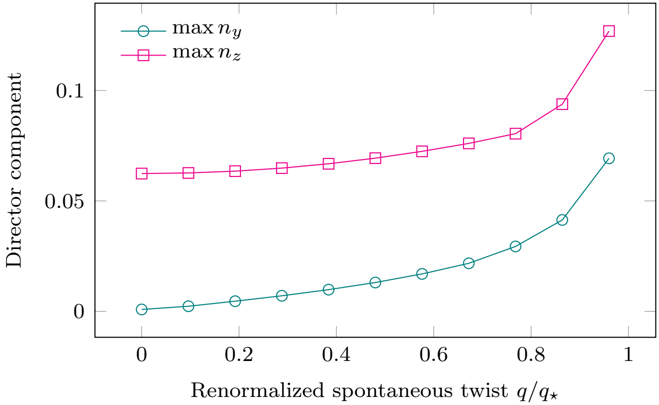


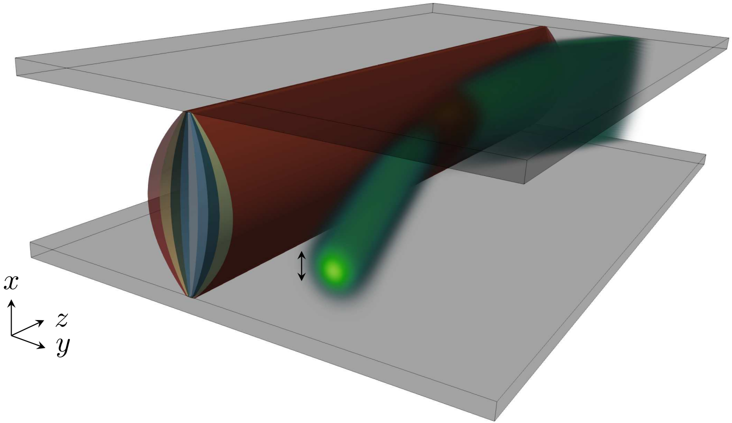
⇒ Potential for low-power non-linear optical photonics devices (e.g. active lenses)

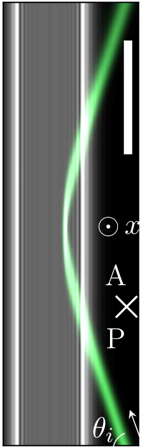
G. Poy *et al.*, *Physical Review Letters* **125** (2020)

Outline

Transmission and/or reflection with line-like structure

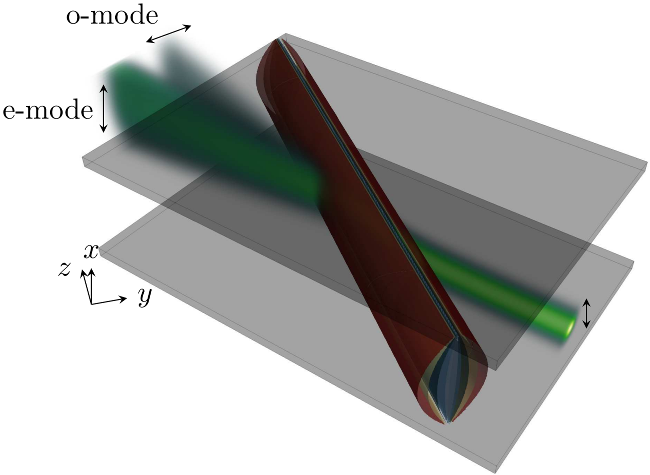
Reflection of incident extraordinary beam ($\theta_i = 70°$):

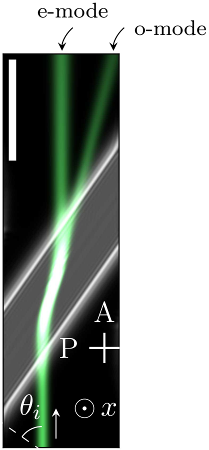




Transmission and/or reflection with line-like structure

Transmission of incident extraordinary beam ($\theta_i = 55°$):





Description with a generalization of Snell's law

From an exact eigenmode decomposition of Maxwell equations:

$$n^{(\alpha,m)} \sin\theta^{(\alpha,m)} = n_i \sin\theta_i$$

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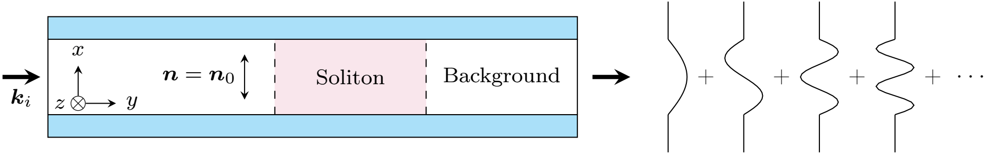
- In our system, $n^{(\alpha,m)}$ = effective index of eigenmode $\{\alpha, m\}$ far from the soliton
  - ⋆ $\alpha = e, o$: polarisation state
  - ⋆ $m = 1, 2, \ldots$: mode index



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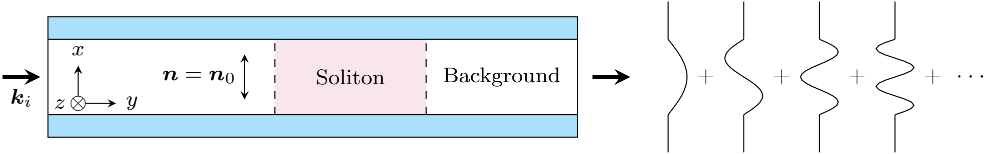
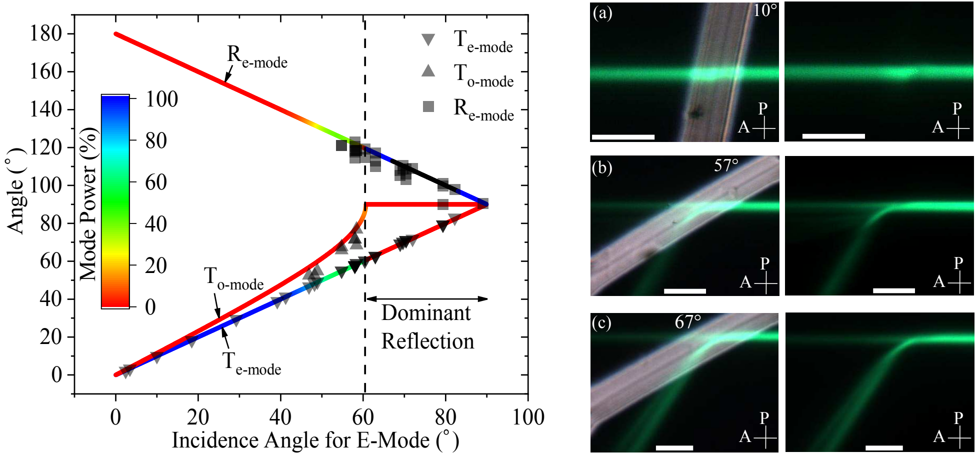


$\theta^{(\alpha,m)}$ does not depends on the choice of topological soliton!
(but Fresnel coefficients do)

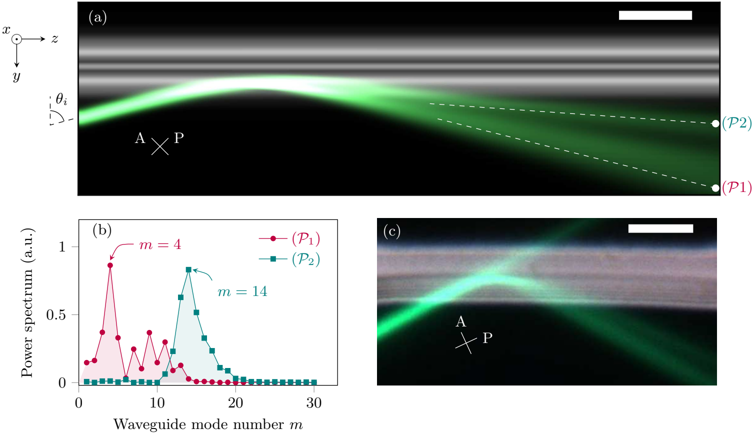
Comparison with experiments

Small mode index approximation in thick samples: $n^{(\alpha,m)} \approx n_\alpha \sqrt{1-(m/m_0)^2} \approx n_\alpha$



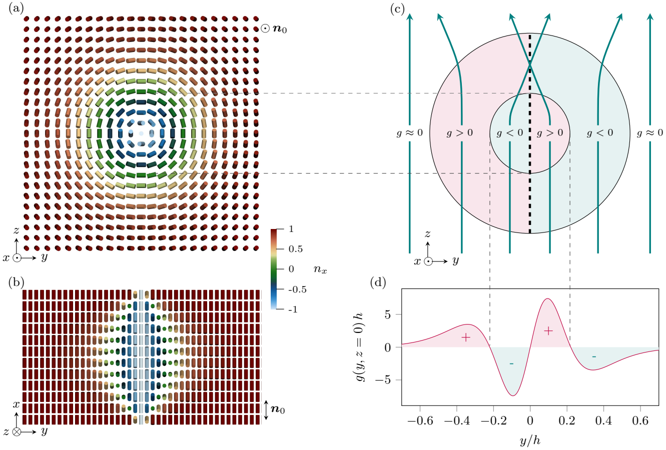
Comparison with experiments

Splitting of eigenmode packets (strongly depends on x-profile): $n^{(\alpha,m_1)} \neq n^{(\alpha,m_2)}$

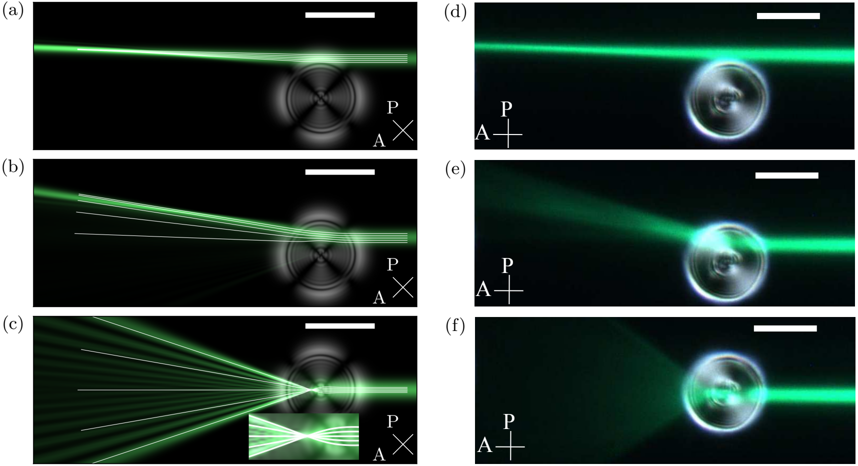


Interaction with point-like topological solitons

Simplification with 2D rays: $\mathrm{d}p_y/\mathrm{d}z \approx -(\epsilon_a/2n_0)\,g$, where $g \equiv \partial n_z^2/\partial y$



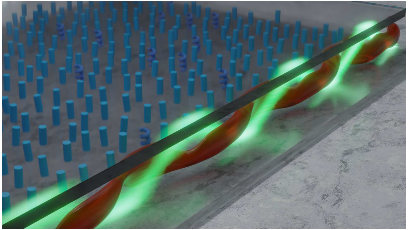
Light deflection and lensing with pinned torons

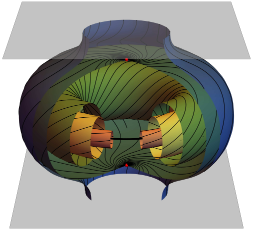


A. Hess *et al.*, *Physical Review X* **10** (2020)

Outline

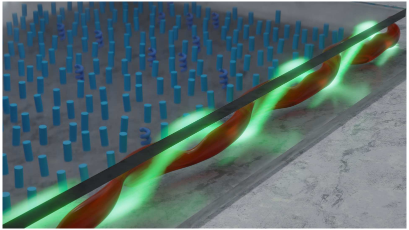
Take-home message

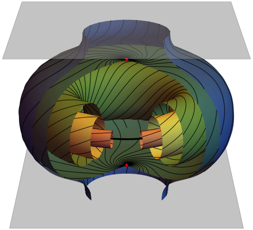




Chirality and soft topological solitons unlocks new possiblities to control the flow of light at the microscopic level

Take-home message

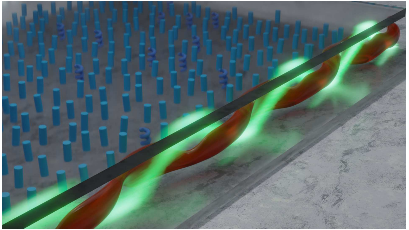


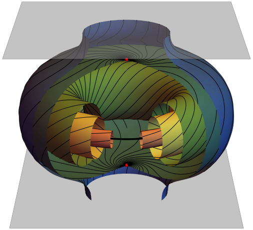


Chirality and soft topological solitons unlocks new possiblities to control the flow of light at the microscopic level

- Chirality-enhanced optical response: towards enriched opto-mechanical interactions

Take-home message

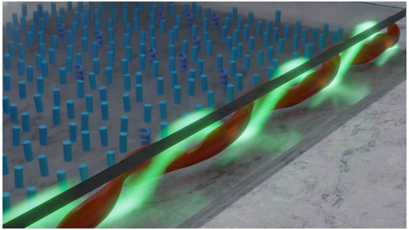


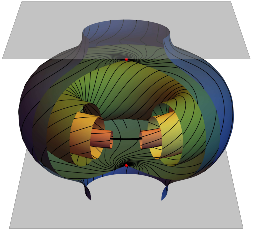


Chirality and soft topological solitons unlocks new possiblities to control the flow of light at the microscopic level

- Chirality-enhanced optical response: towards enriched opto-mechanical interactions
- Matter transforming light, light transforming matter: what happens when we combine everything?

Take-home message





Chirality and soft topological solitons unlocks new possiblities to control the flow of light at the microscopic level

- Chirality-enhanced optical response: towards enriched opto-mechanical interactions
- Matter transforming light, light transforming matter: what happens when we combine everything?

Next step: establishment of a general chirality-enhanced topological optomechanics framework.