XXXI Cycle
PhD in Physics

Spontaneous photonic lattices and non-linear waves in disordered ferroelectrics

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UNIVERSITÀ DI ROMA

Summary

- Diffraction
- Photorefractive Effect
- Relaxors
- Optical Spatial Soliton
- Scale-Free Optics

- Super-Crystals
- Anomalous Birefringence
- Nonlinear Bessel Beam
- Knife-Edge Super-Resolution

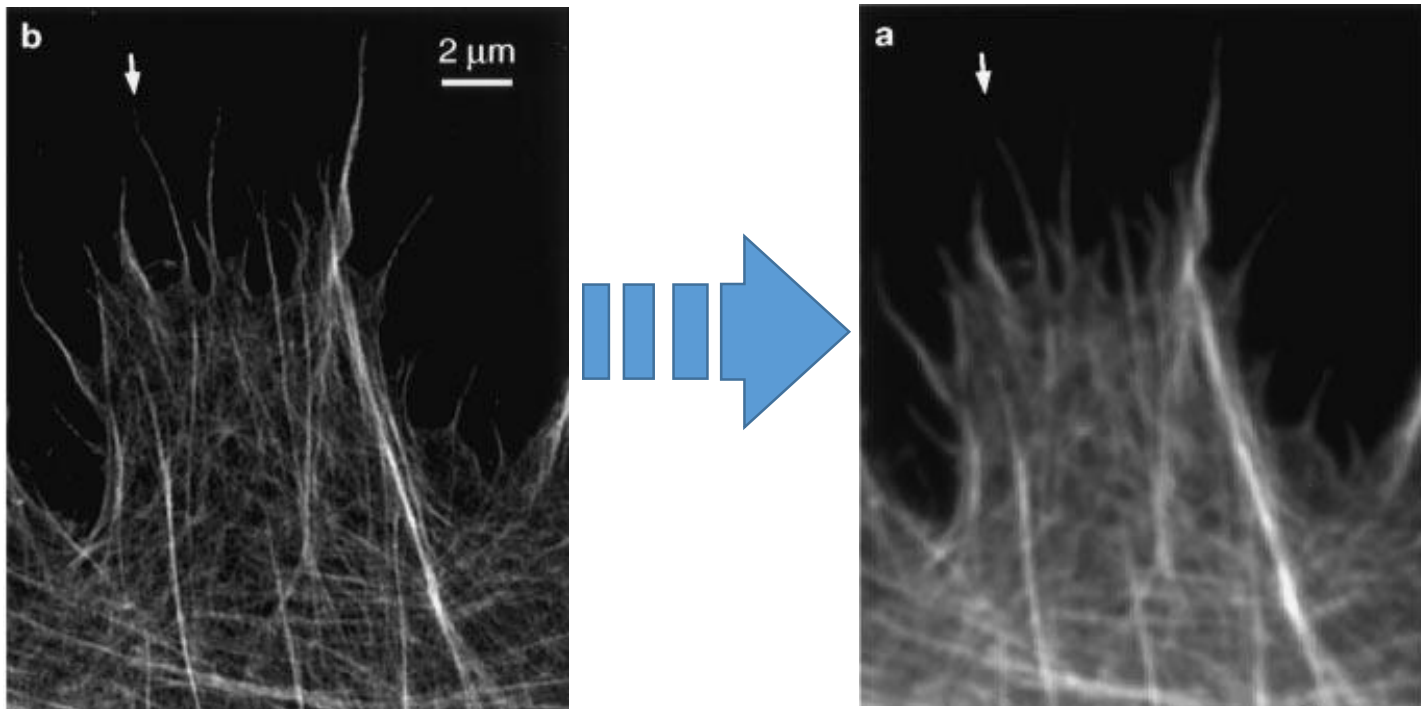
Diffraction

M. G. L. Gustafsson, *J. Microsc.* **198**, 82-87 (2000)

- Depends on wavelength λ
- Limits the resolution of an optical system to $\frac{\lambda}{2NA}$
- Is a property of propagating waves also in vacuum

$$i\partial_z A + \frac{1}{2k}\nabla_\perp^2 A = 0$$

Linear Helmholtz equation



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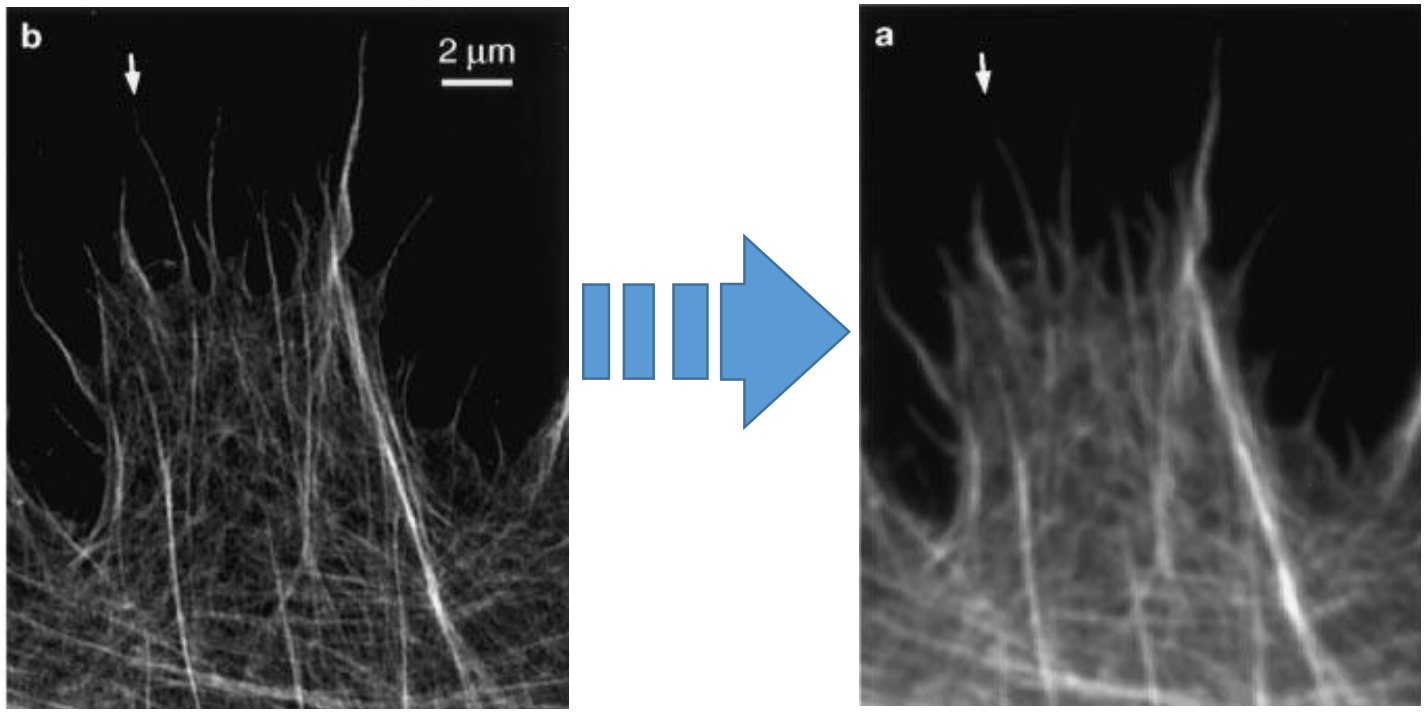


$$i\partial_z A + \frac{1}{2k}\nabla_\perp^2 A = 0$$

Linear Helmholtz equation

But it can be overcome:

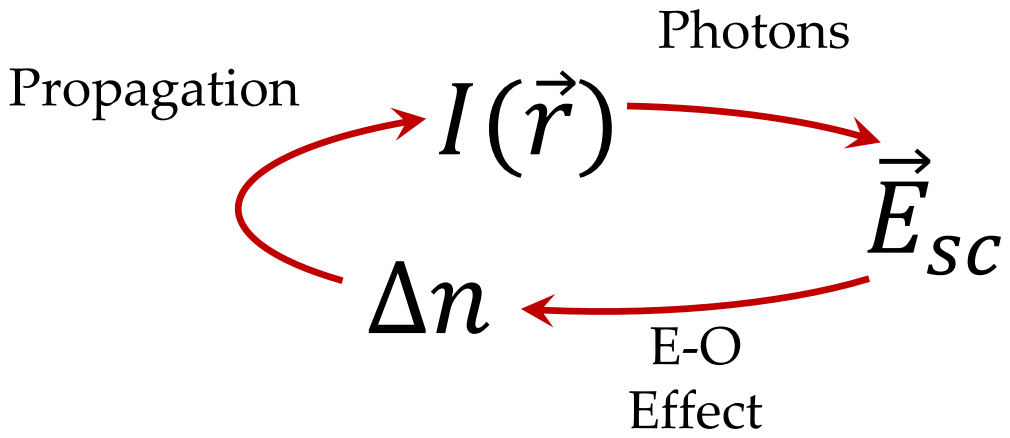
Nonlinearity

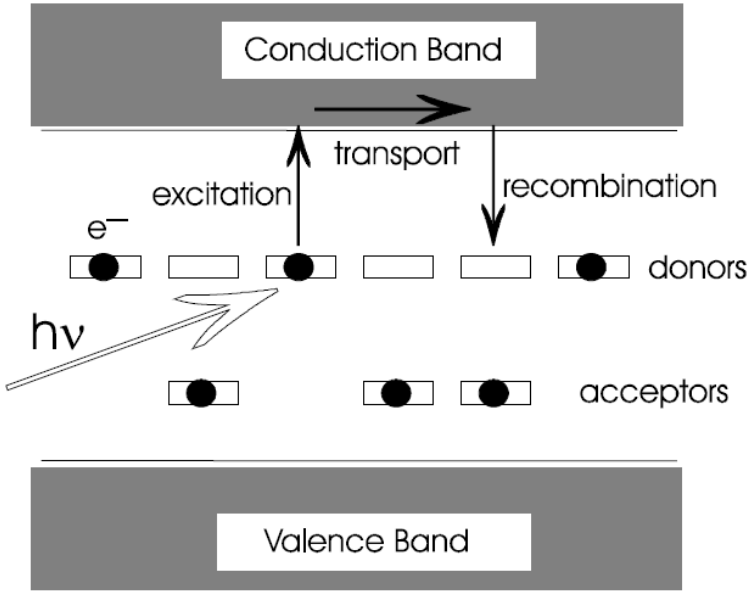
$$i\partial_z A + \frac{1}{2k}\nabla_\perp^2 A + \frac{k}{n}\Delta n A = 0$$

Nonlinear Helmholtz Eq. (NLSE)

Photorefractive Effect

Nonlinear optics effect which modifies locally the material refractive index because it generates a spatial electric field E_{SC} due to the generation of impurities photoexcitation





E. DelRe, et al., *Progress in Optics* **53**, 153–200 (2009)

$$\Delta n_{PR} = -\frac{1}{2} n^3 g_{eff} \epsilon_0^2 (\epsilon_r - 1)^2 E_{sc}$$

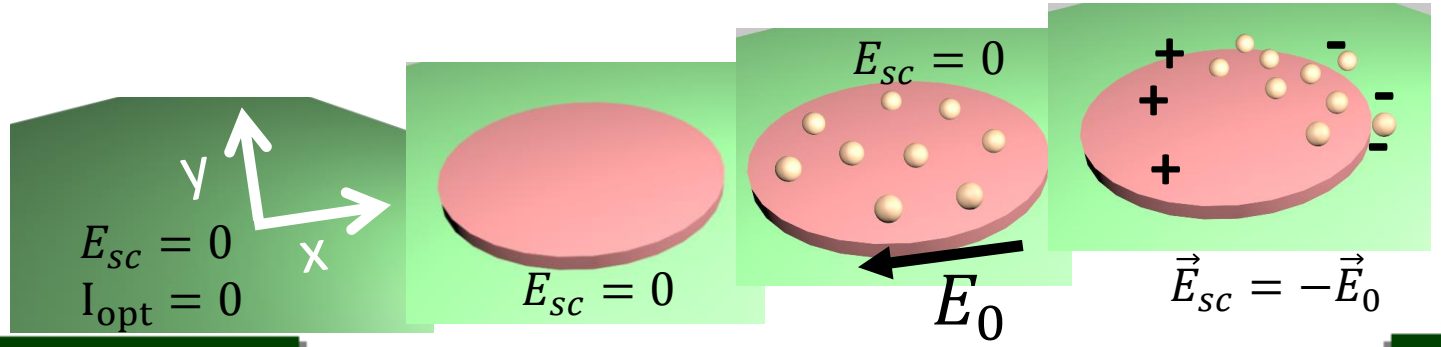
Saturable Kerr nonlinearity

$$E_{sc} = \frac{E_0}{(1 + I/I_B)}$$

Cumulative process

↓

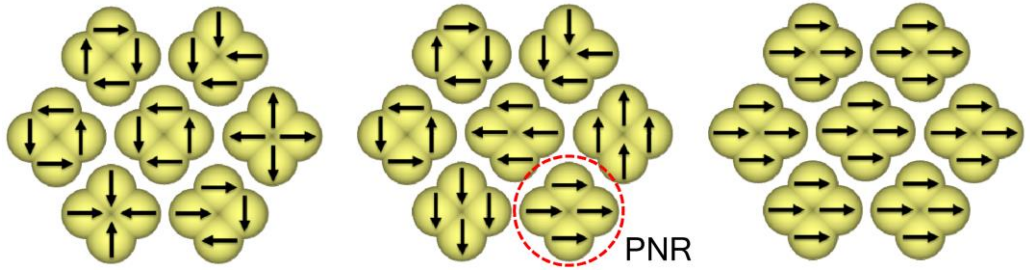
Low optical power



Relaxors

Y. C. Chang, et al., *Optics Letters*, **38**, 4574-4577 (2013)

Relaxors are complex ferroelectrics, it means that they have a compositional disorder whereby an element in the unitary cell is randomly replaced with another.

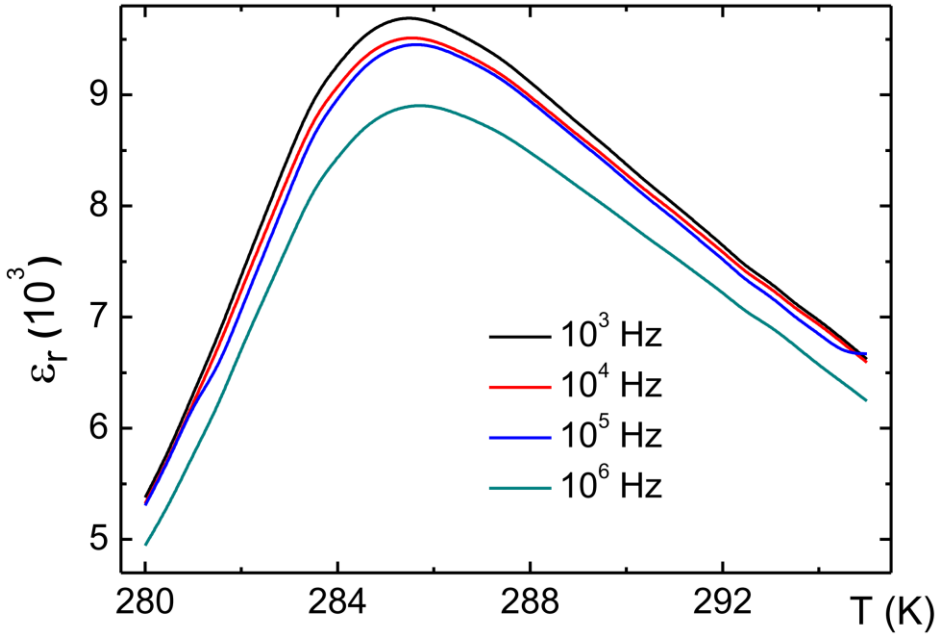


$T \gg T_C$ Paraelectric Phase

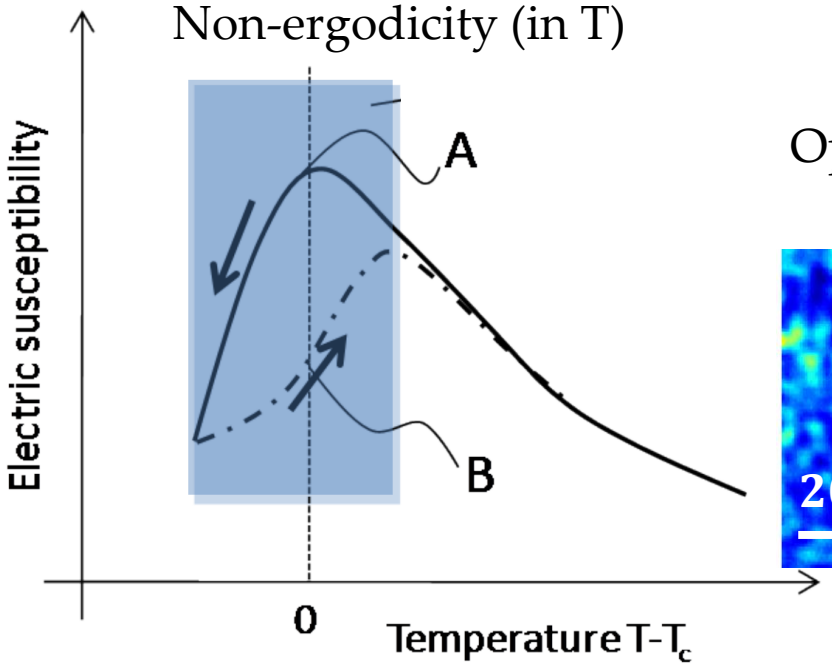
$T \simeq T_C$ Paraelectric Phase with PNR

$T \ll T_C$ Ferroelectric Phase

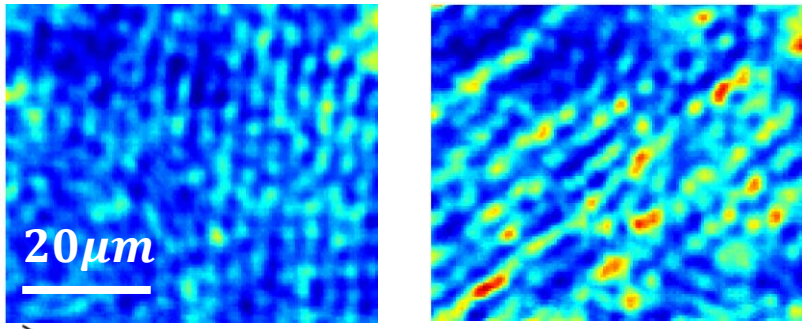
Diffuse Transition with Giant electro-optic response



Non-ergodicity (in T)



Optical transparency due to the sub-wavelength dimension of PNRs



D. Pierangeli, et al., *Opt. Mat. Express*, **4**, 1487-1493

Optical spatial solitons

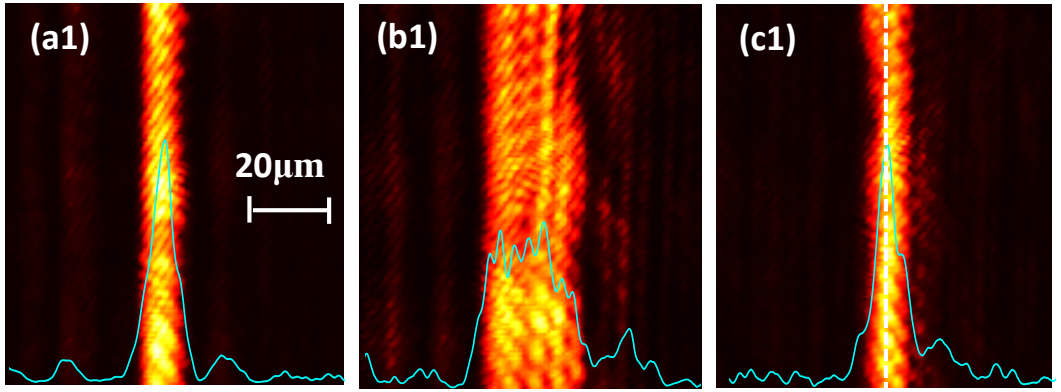
Stationary solutions of NLSE when a nonlinearity compensates the diffraction

$$\frac{\partial \vec{A}_\omega}{\partial z} + \frac{i}{2k}\nabla_\perp^2 \vec{A}_\omega = -ik\frac{\Delta n(I)}{n_o}\vec{A}_\omega$$

and, for 1D beam:

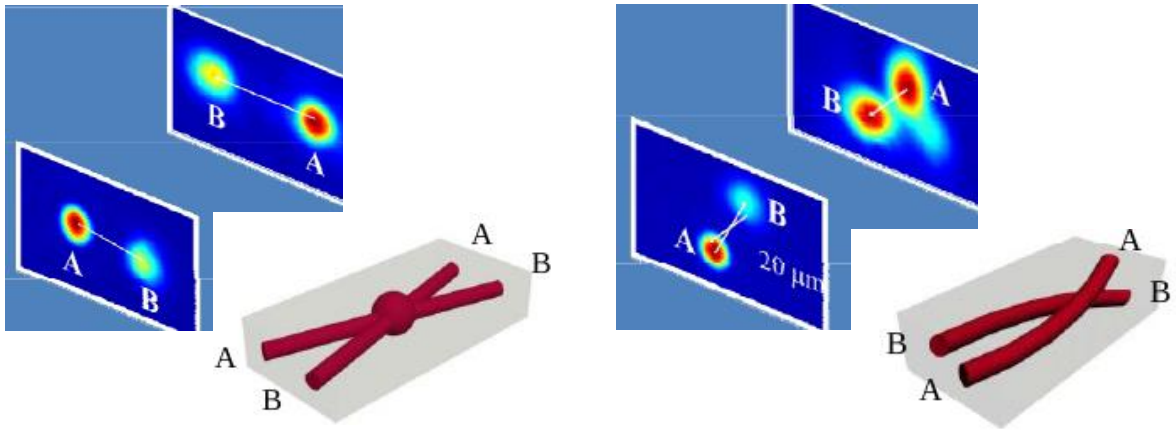
$$A(x,z) = u(x)e^{i\Gamma z}\sqrt{I_b}$$

1D soliton

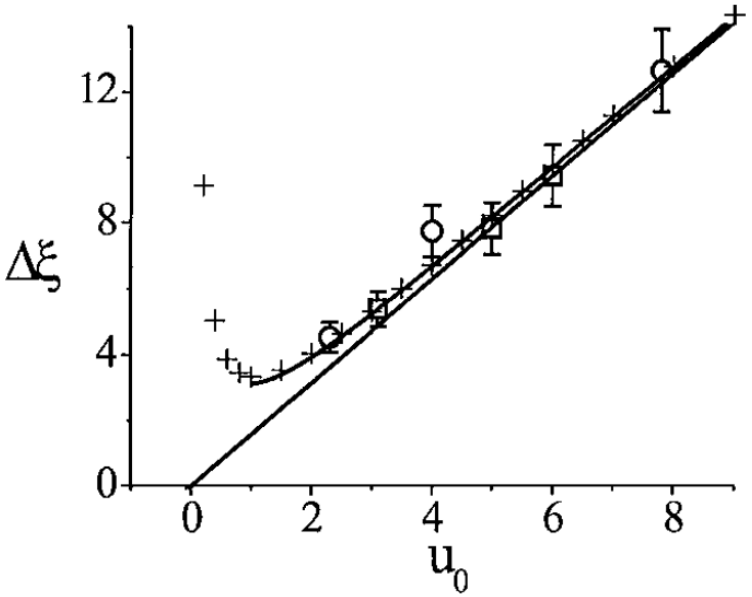


INPUT | OUTPUT DIFFRACTION | OUTPUT SOLITON

Soliton-soliton interaction

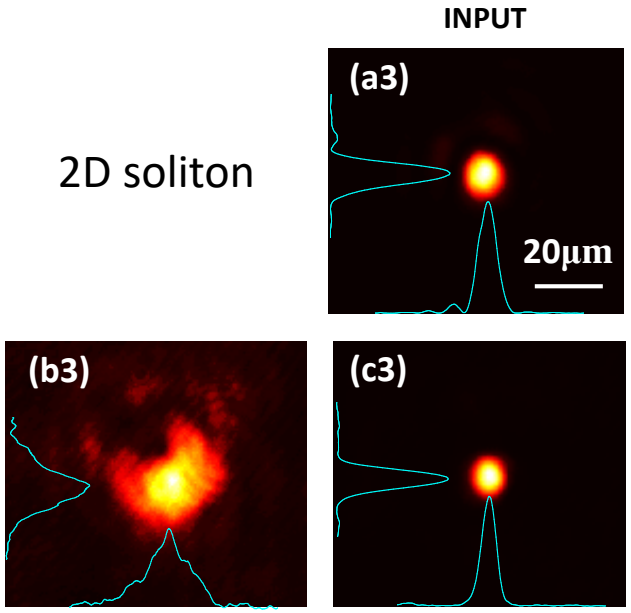


Existence curve



E. DelRe, et al., *Opt. Lett.* **28**, 260-262 (2003)

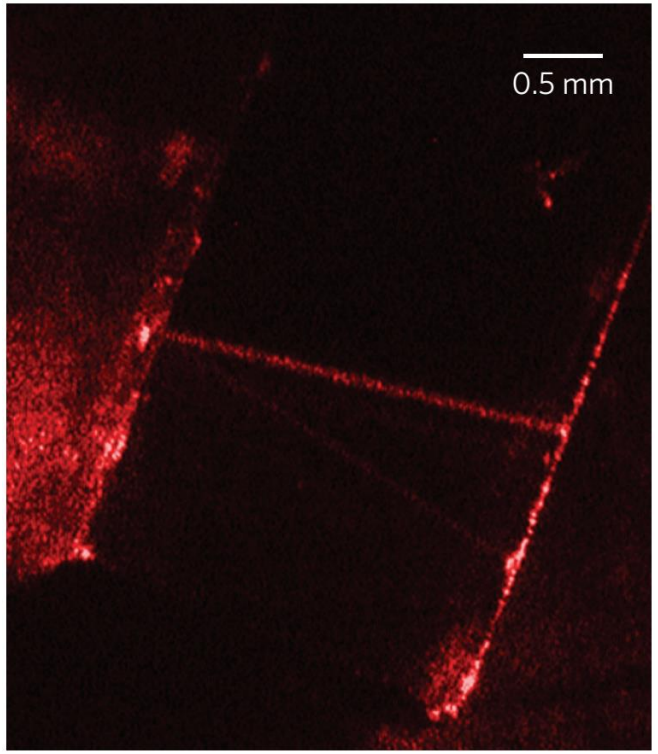
2D soliton



INPUT | OUTPUT DIFFRACTION | OUTPUT SOLITON

D. Pierangeli, et al., *Phys. Rev. Lett.* **114**, 203901 (2015)

Scale Free Optics



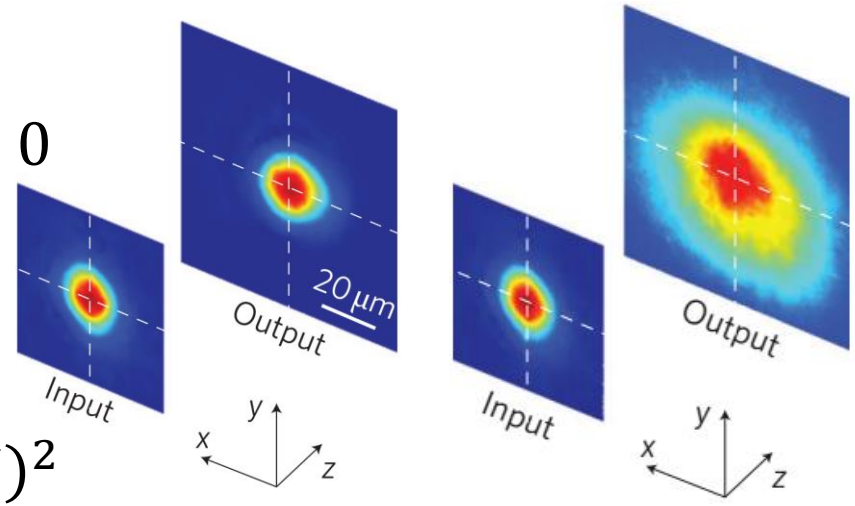
E. DelRe, et al. *Nat. Phot.* (2015)

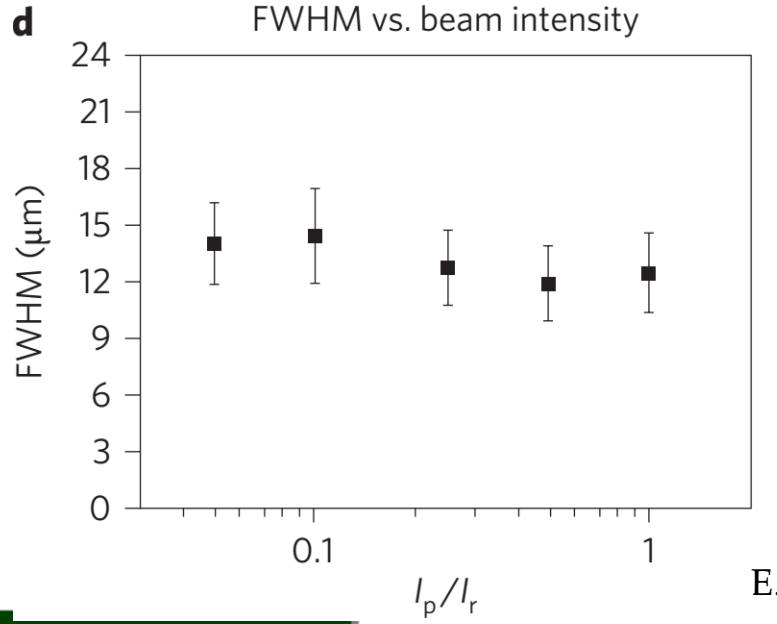
This effect allows the propagation of sub-wavelength beam

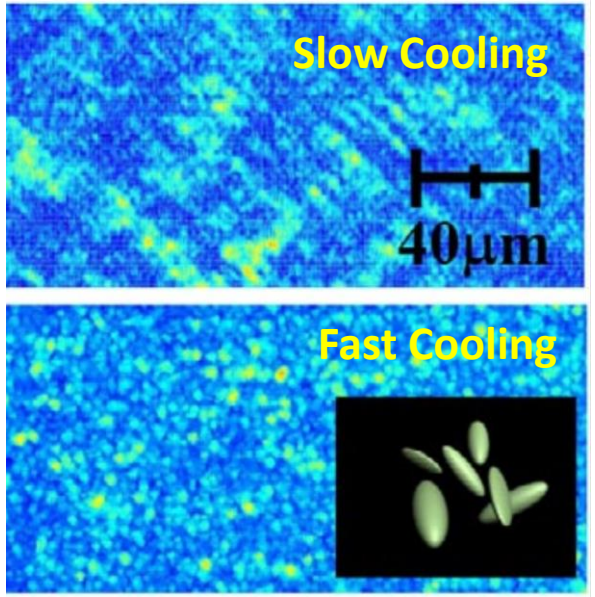
$$i\partial_z A + \frac{1}{2k}\nabla_\perp^2 A + \frac{k}{n}\Delta n A = 0$$

High cooling rate α
(Fast cooling)

$$\Delta n_{SF} = -\frac{n}{k^2}\left(\frac{L(\alpha)}{\lambda}\right)^2 \frac{(\nabla_\perp I)^2}{4I^2}$$



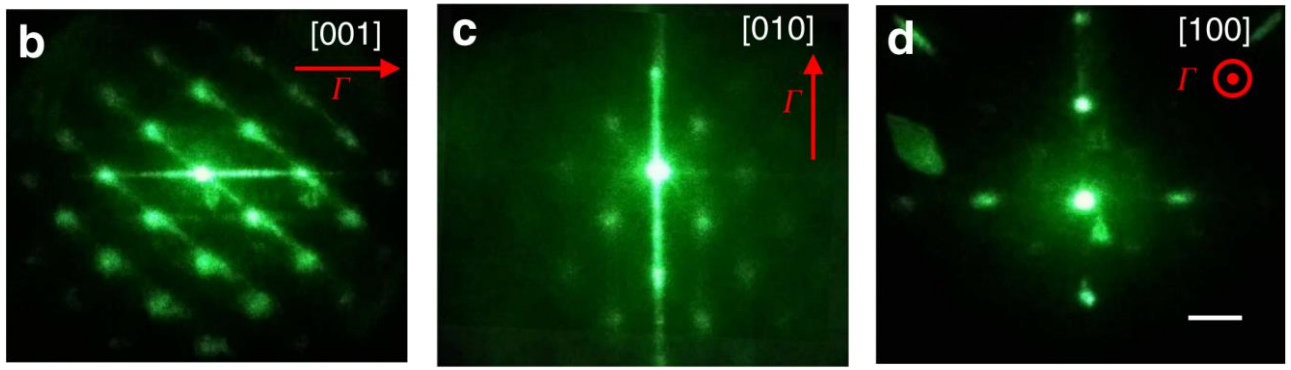




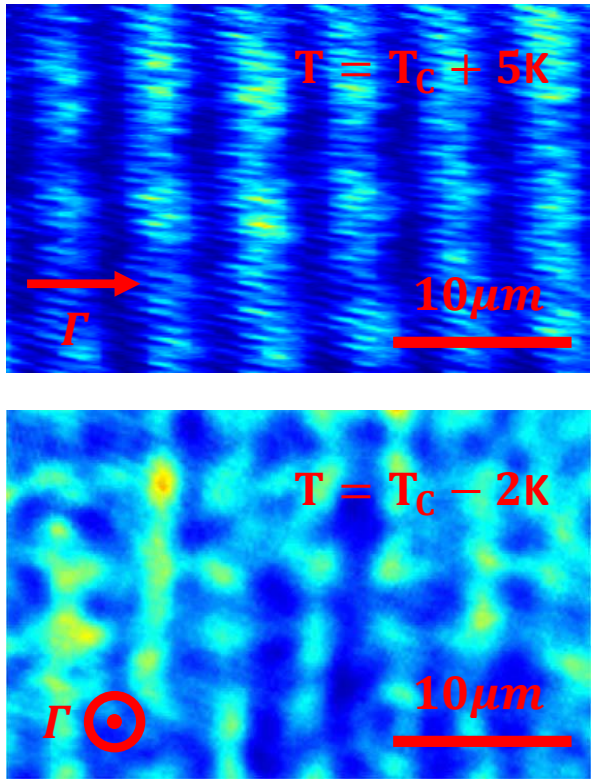
E. DelRe, et al. *Nat. Phot.* **5** 39-42 (2011)

Super-Crystals

D. Pierangeli, et al., *Nat. Comm.* **7**, 10674 (2016)

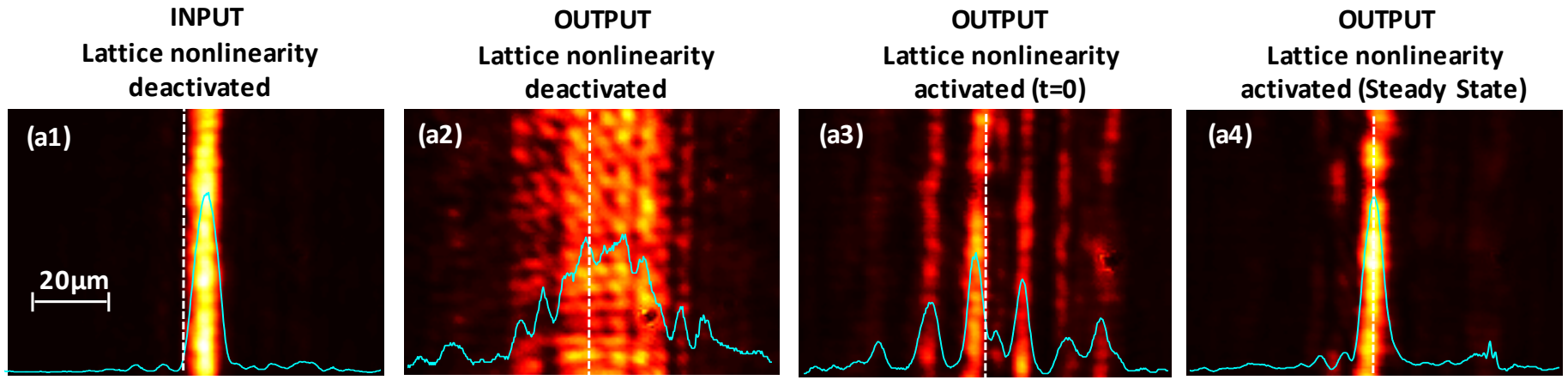


A spontaneous 3D lattice with a lattice constant that is more than 10^4 times larger than that of the underlying perovskite 1D lattice



The samples composition varies slightly along the growth axis due to periodic change of growth temperature. The periodic composition causes a periodic modulation of the linear and nonlinear optical response.

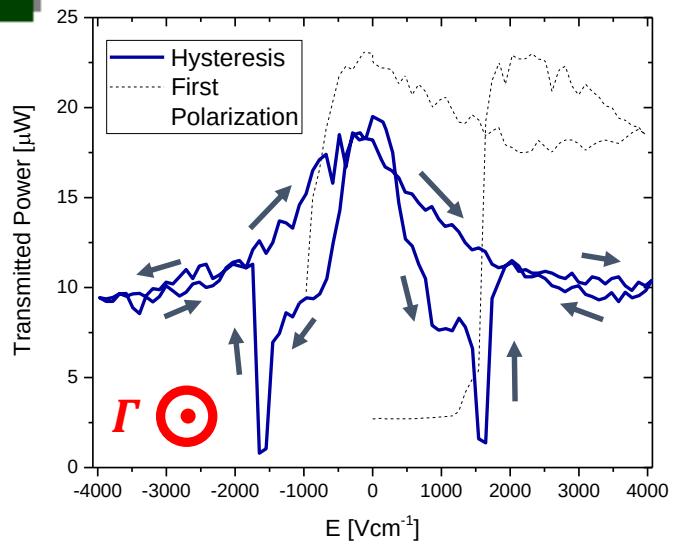
New photorefractive nonlinear lattice that disappears in time

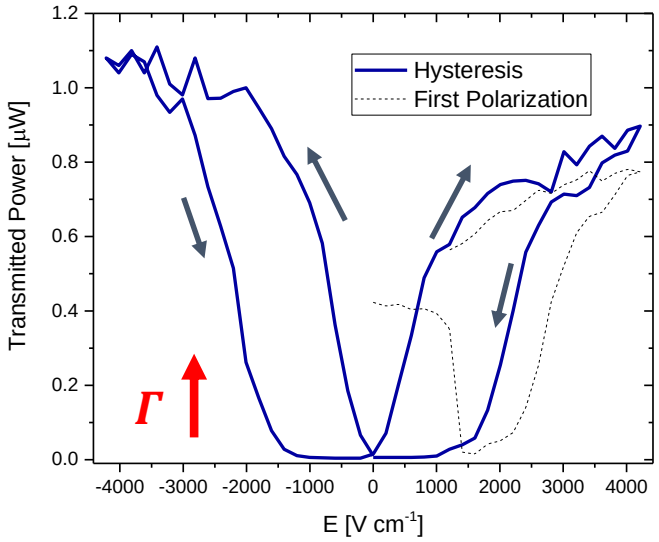


D. Pierangeli, et al., *Phys. Rev. Lett.* **114**, 203901 (2015)

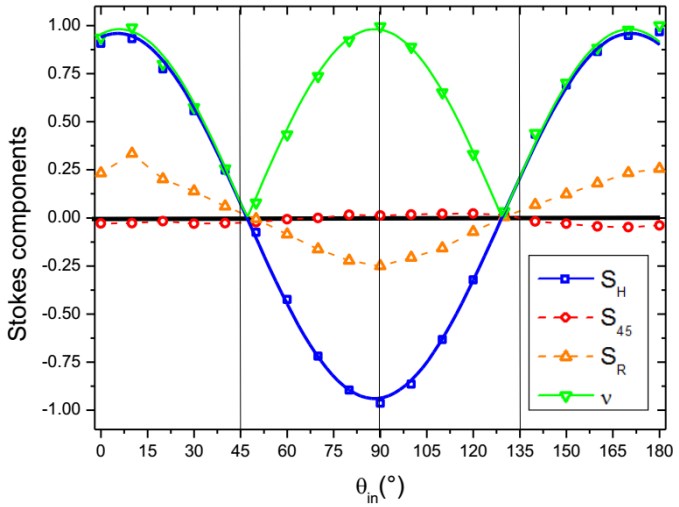
Anomalous Birefringence

Different hysteresis are observed for different orientations when an external bias field is applied on the sample

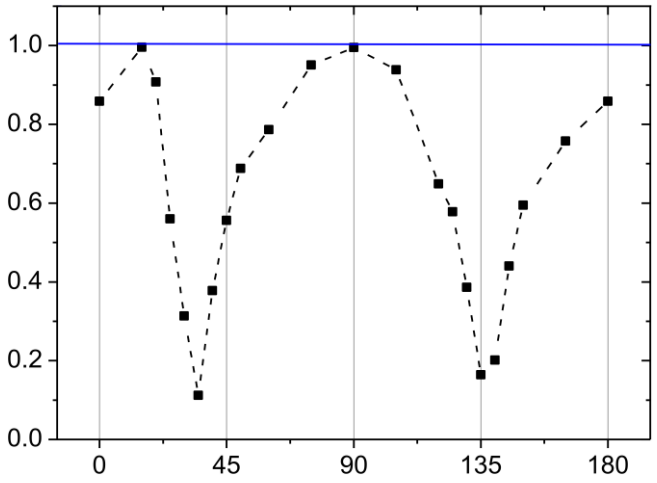




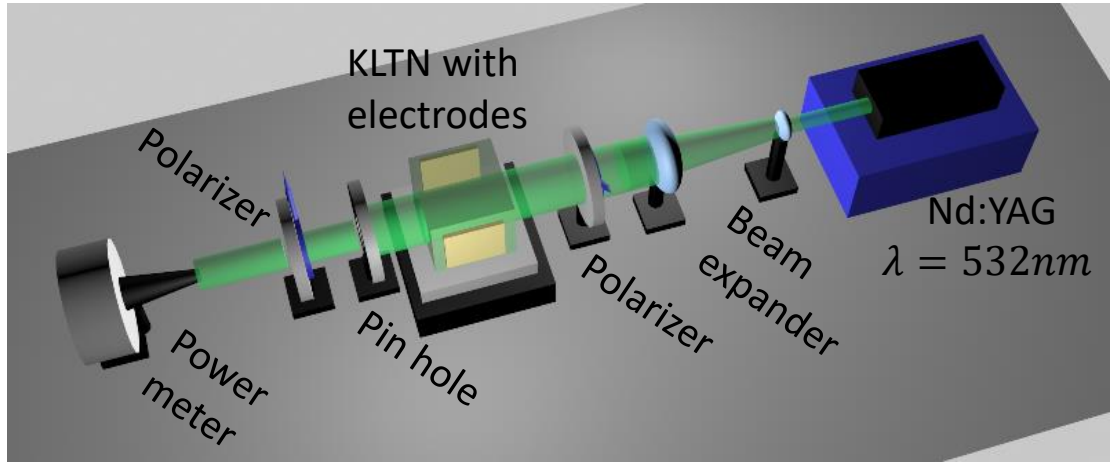
Stokes Parameters



Malus Law Violation



Anomalous phenomena with some depolarization effect for zero external bias field



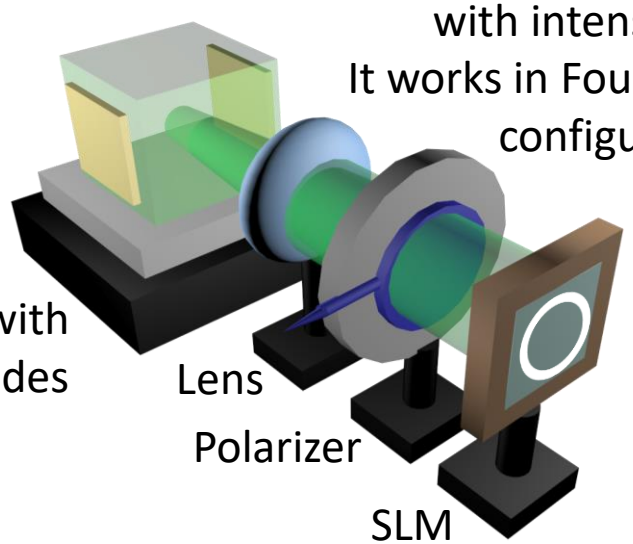
Nonlinear Bessel Beam

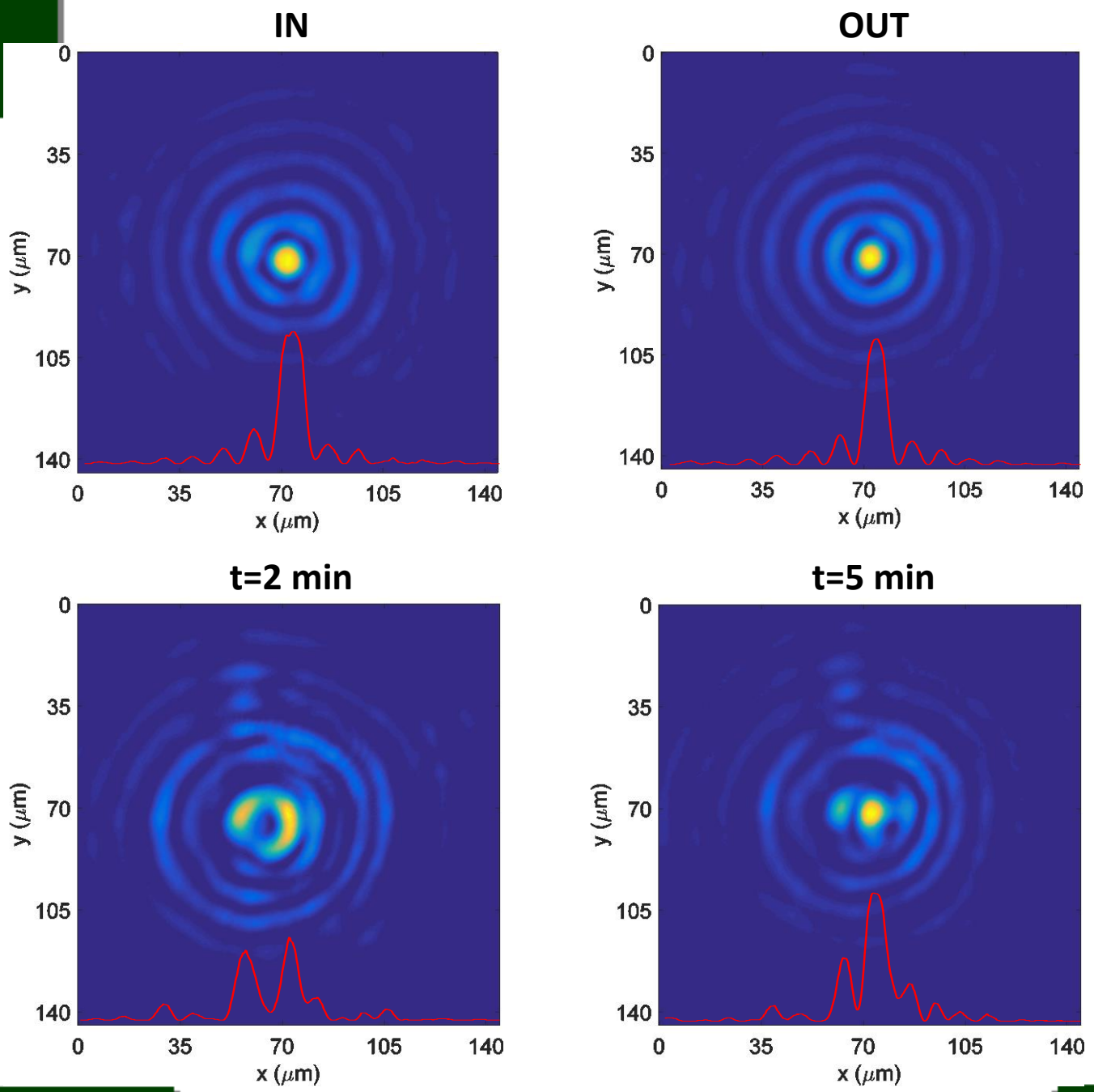
Bessel Beam equation:

$$E(r,\phi,z) = A_0 \exp(ik_z z) J_n(k_r r) \exp(\pm in\phi)$$

Propagation in photorefractive crystal

Spatial Light Modulator (SLM) with intensity mask. It works in Fourier Transform configuration

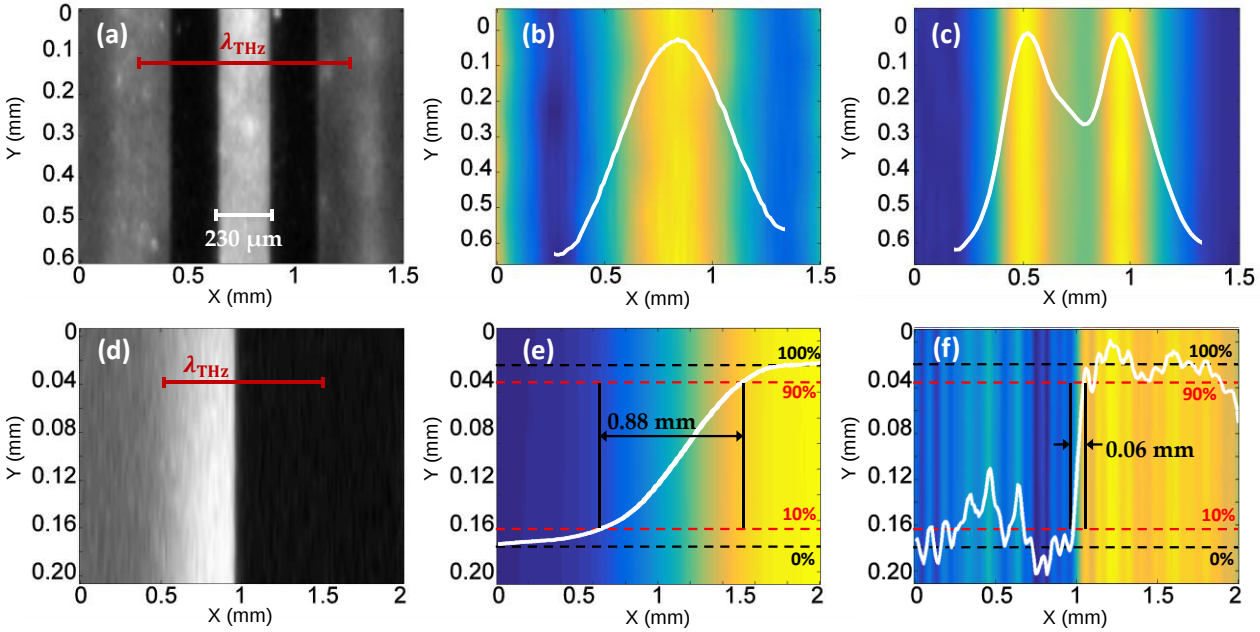


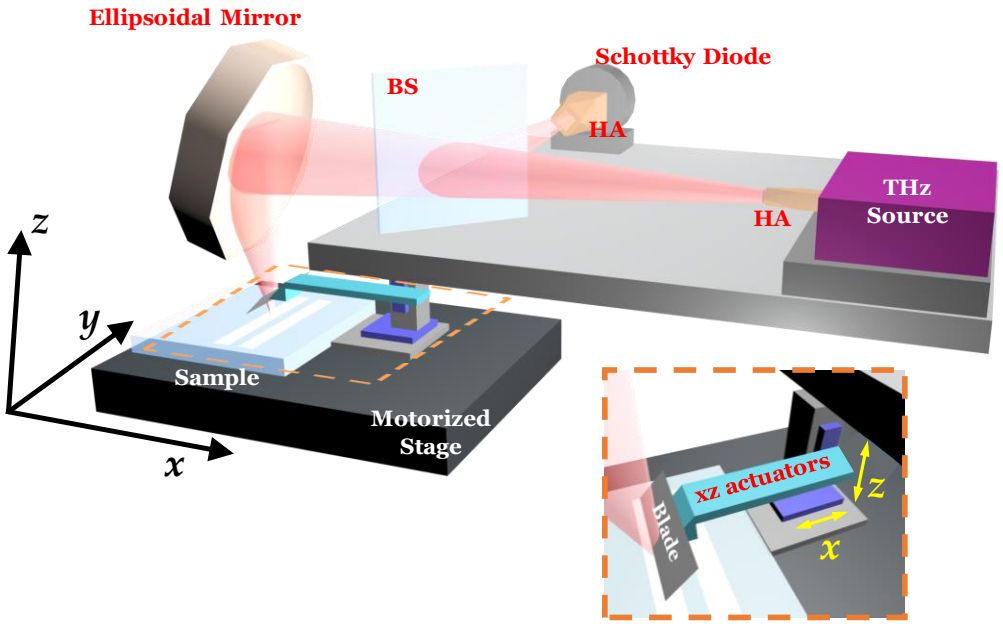


Knife-edge super-resolution

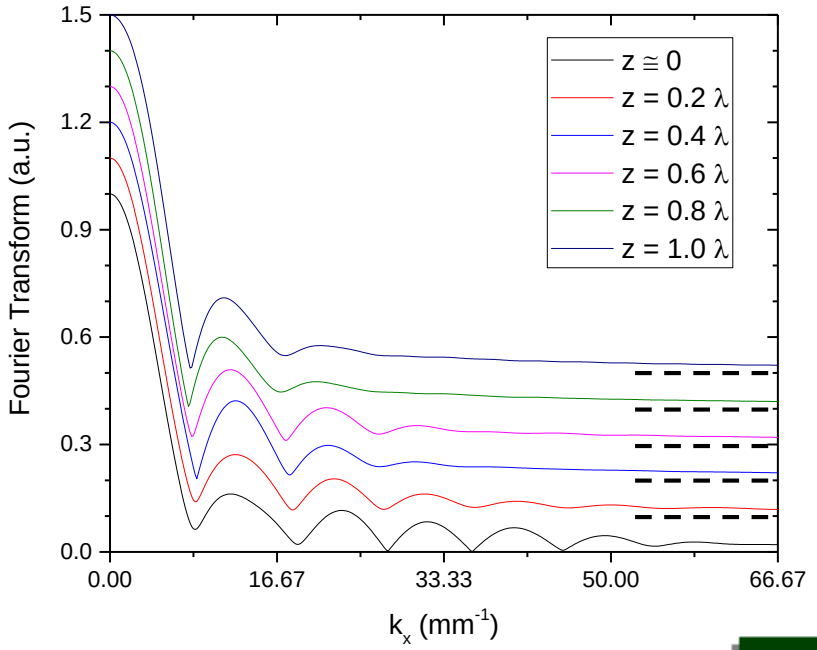
It is a kind of nonlinear imaging which needs at least two photons to reconstruct an image with subwavelength details.

$$I(x,z) = -\int_{\mathbb{R}} I(u,z)\frac{d}{dx'}\theta(u-x')du$$





The experiments, conducted at THz frequencies, thanks to a collaboration with Prof. M. Ortolani, allow to explore easily the near-field



M.Flammini, E.Pontecorvo, V.Giliberti, M.Ortolani, E.DelRe, *Submitted*

Current experiments

➢Characterize the super-crystal samples:

- Understanding the importance of the crystal growth method and composition in the formation of the super-crystal;
- Linking the role of the PNRs with the properties of the super-crystal;
- Highlighting the influence of an applied electric field on the super-crystal;

➢Study the propagation of nonlinear waves:

- Controlling the shape and intensity of optical beams (especially using SLM);
- Investigating the interaction of super-crystals and nonlinear waves;
- Exploring new nonlinear phenomena in 3D photonic bandgap.

Collaborations:

- A. J. Agranat at Hebrew University of Jerusalem
- G.B. Parravicini at University of Pavia