SPIE Quantum Communications and Quantum Imaging VI
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Control of spatial quantum fluctuations using photonic crystals

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CSIC UIB

MOTIVATION

QUANTUM STATES OF LIGHT
IN OPTICAL PATTERNS

MOTIVATION

QUANTUM OPTICS

QUANTUM STATES OF LIGHT IN OPTICAL PATTERNS

SELF-ORGANIZATION IN COMPLEX SYSTEMS

AIM → study the possibility to *control* the state of light emitted by optical parametric oscillator using *photonic crystals*

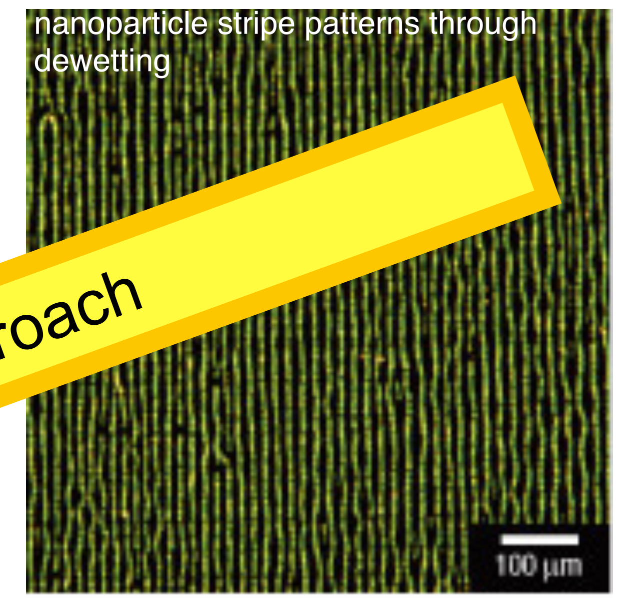
OUTLINE

- OPTICAL PATTERN FORMATION: FROM CLASSICAL TO QUANTUM
- PHOTONIC CRYSTALS
- THE MODEL: OPO WITH PC
- RAISING AND LOWERING THE PARAMETRIC THRESHOLD
- PC AND QUANTUM IMAGES
- TWIN BEAMS
- CONSERVATION OF MOMENTUM
- CONCLUSIONS AND OUTLOOK

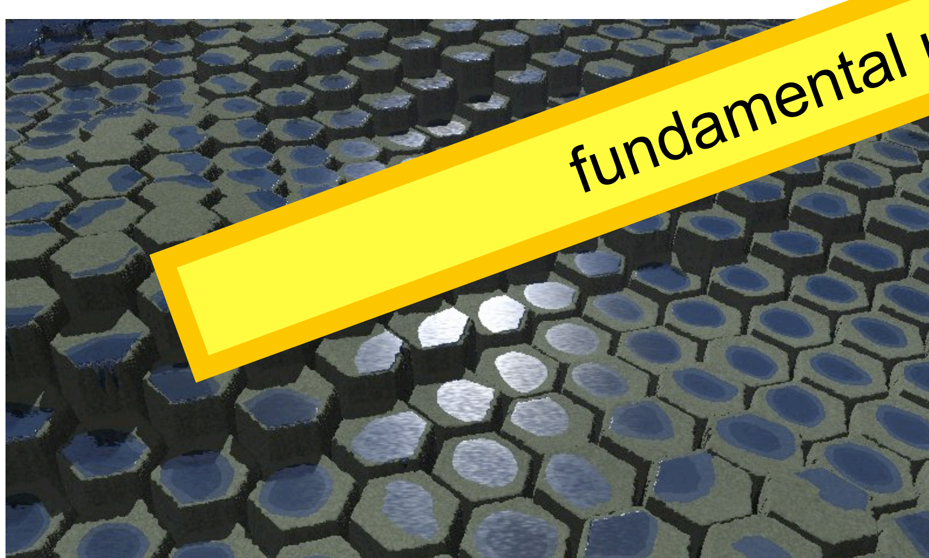
PATTERN FORMATION

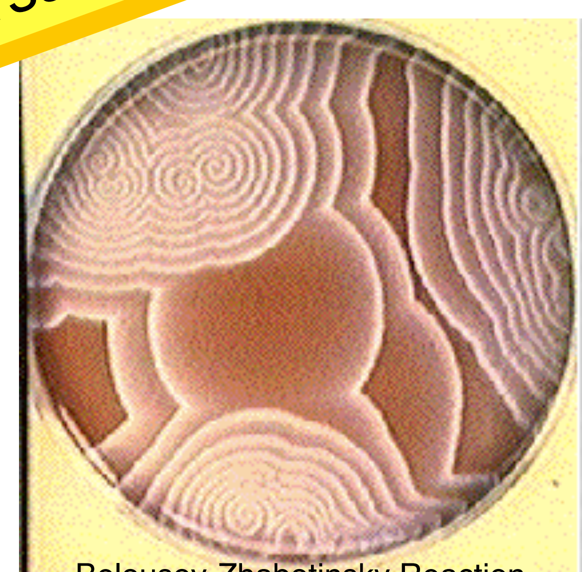
self-organization phenomenon in complex systems, arising from the interplay between nonlinear dynamics and spatial coupling in systems out of equilibrium

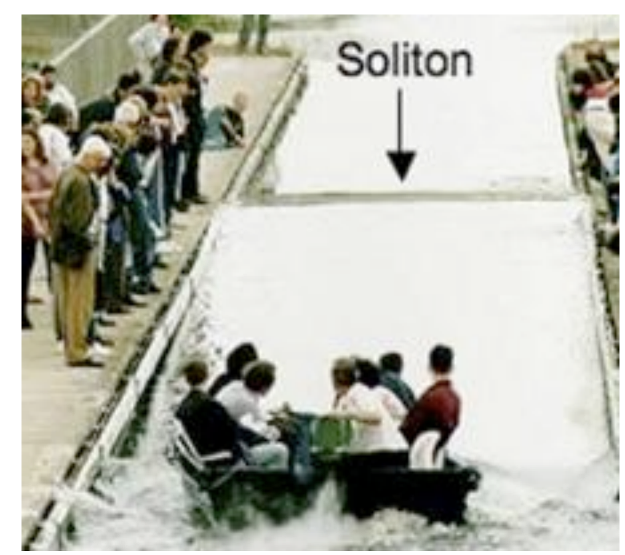
Haken ‘74, Nicolis & Prigogine ‘77



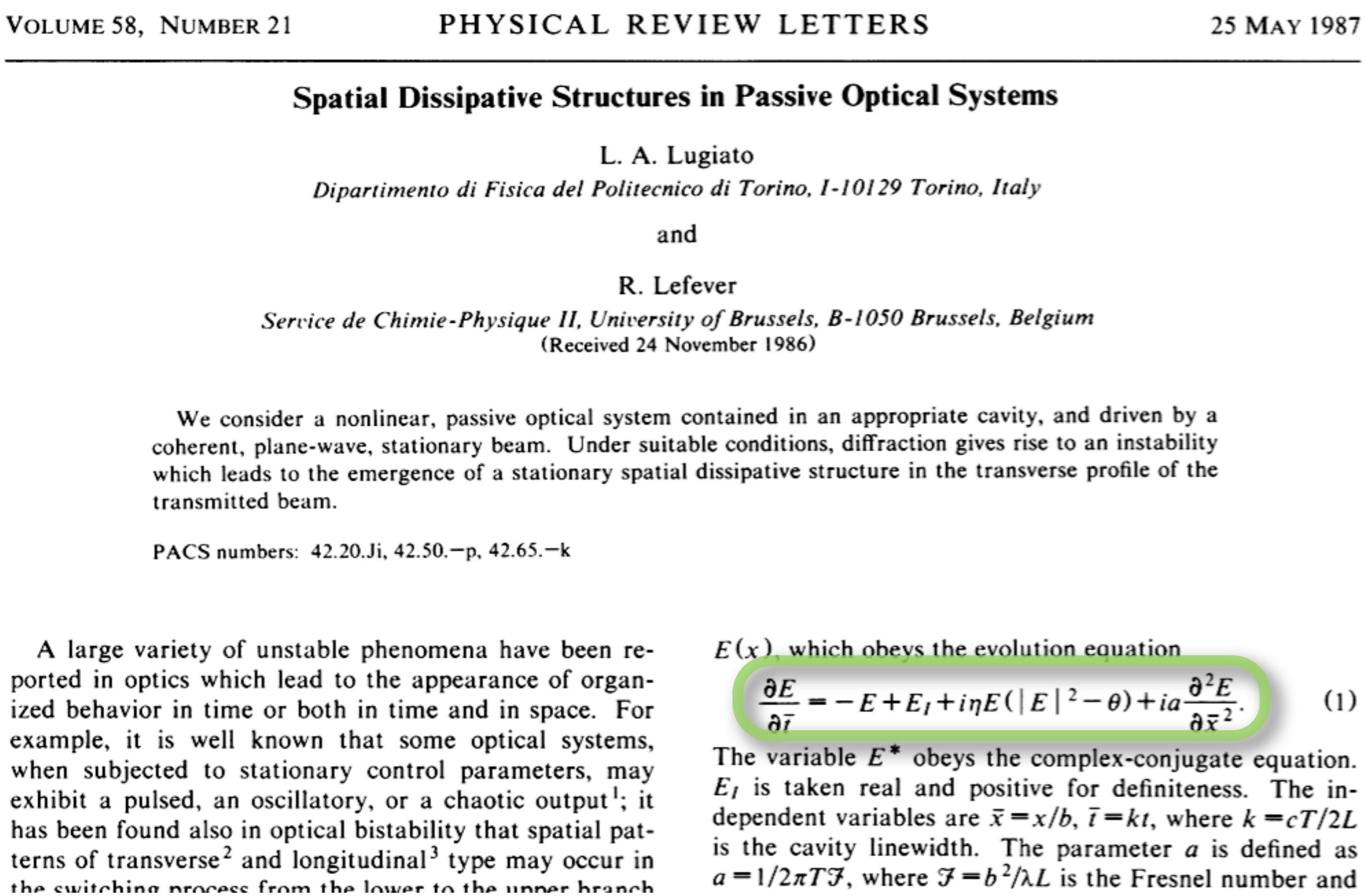
fundamental universal character, unified approach







OPTICAL PATTERN FORMATION


VOLUME 58, NUMBER 21 PHYSICAL REVIEW LETTERS 25 MAY 1987

Spatial Dissipative Structures in Passive Optical Systems

L. A. Lugiato
Dipartimento di Fisica del Politecnico di Torino, I-10129 Torino, Italy

and

R. Lefever
Service de Chimie-Physique II, University of Brussels, B-1050 Brussels, Belgium
(Received 24 November 1986)

We consider a nonlinear, passive optical system contained in an appropriate cavity, and driven by a coherent, plane-wave, stationary beam. Under suitable conditions, diffraction gives rise to an instability which leads to the emergence of a stationary spatial dissipative structure in the transverse profile of the transmitted beam.

PACS numbers: 42.20.Ji, 42.50.−p, 42.65.−k

A large variety of unstable phenomena have been reported in optics which lead to the appearance of organized behavior in time or both in time and in space. For example, it is well known that some optical systems, when subjected to stationary control parameters, may exhibit a pulsed, an oscillatory, or a chaotic output[1]; it has been found also in optical bistability that spatial patterns of transverse[2] and longitudinal[3] type may occur in the switching process from the lower to the upper branch

$E(x)$, which obeys the evolution equation

$$\frac{\partial E}{\partial \bar{t}} = -E + E_I + i\eta E(|E|^2 - \theta) + ia\frac{\partial^2 E}{\partial \bar{x}^2}. \qquad (1)$$

The variable E^* obeys the complex-conjugate equation. E_I is taken real and positive for definiteness. The independent variables are $\bar{x} = x/b$, $\bar{t} = kt$, where $k = cT/2L$ is the cavity linewidth. The parameter a is defined as $a = 1/2\pi T\mathcal{F}$, where $\mathcal{F} = b^2/\lambda L$ is the Fresnel number and

theory: existence of solutions, stability, amplitude equations; patterns, solitons, defects, vortices....

OPTICAL PATTERN FORMATION

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cavity losses, driving field, diffraction

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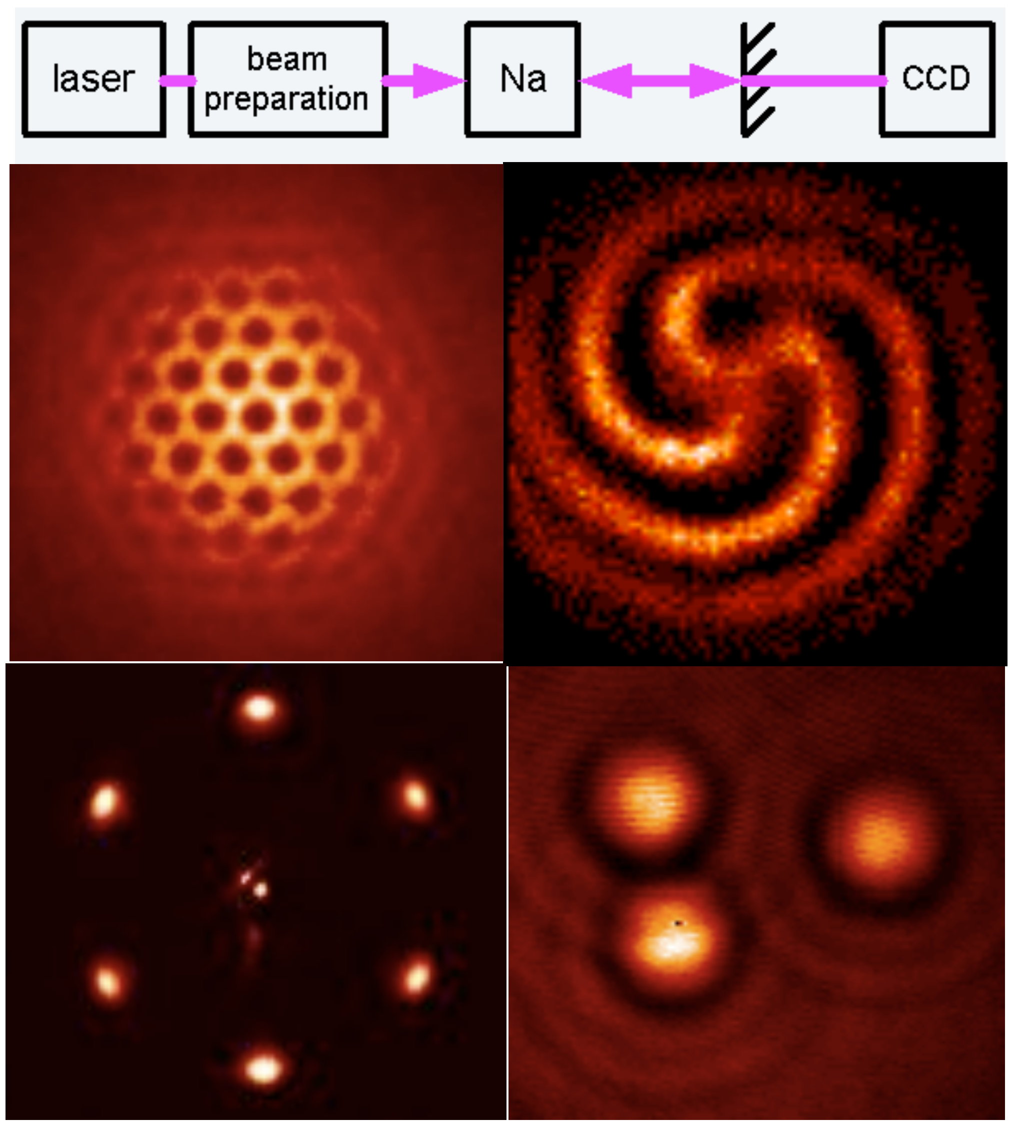
OPTICAL PATTERN FORMATION

experiments: fast temporal scales, size, quality, control of conditions, direct access FF...

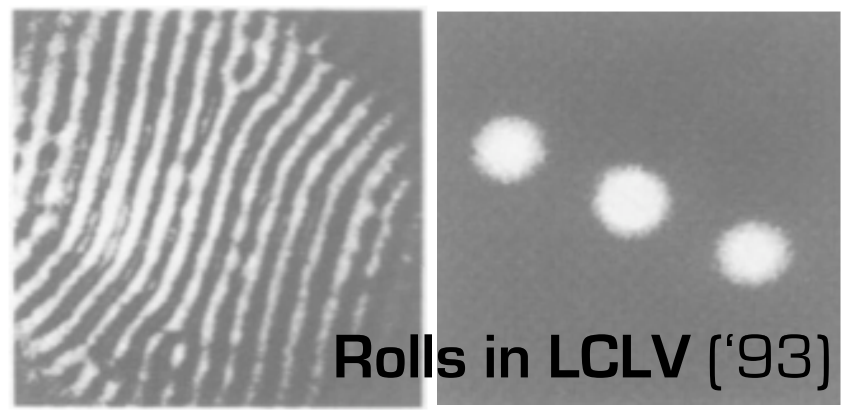
OPTICAL PATTERN FORMATION

experiments: fast temporal scales, size, quality, control of conditions, direct access FF...

Lange' group in Münster



Istituto Nazionale di Ottica

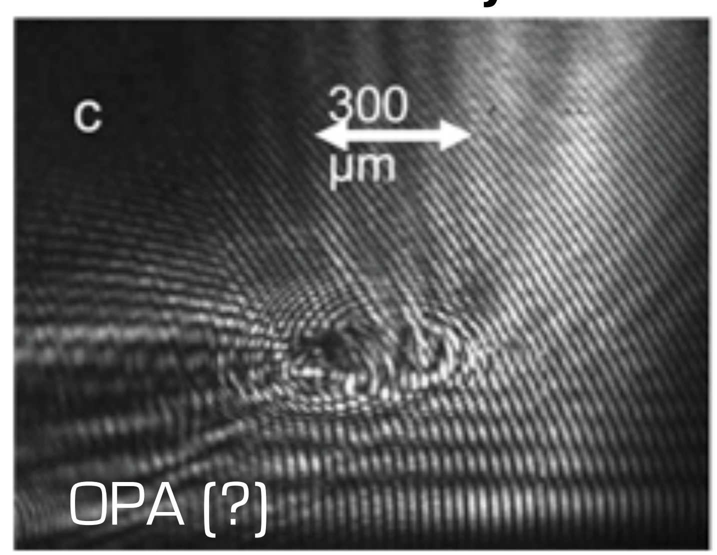


Rolls in LCLV ('93)

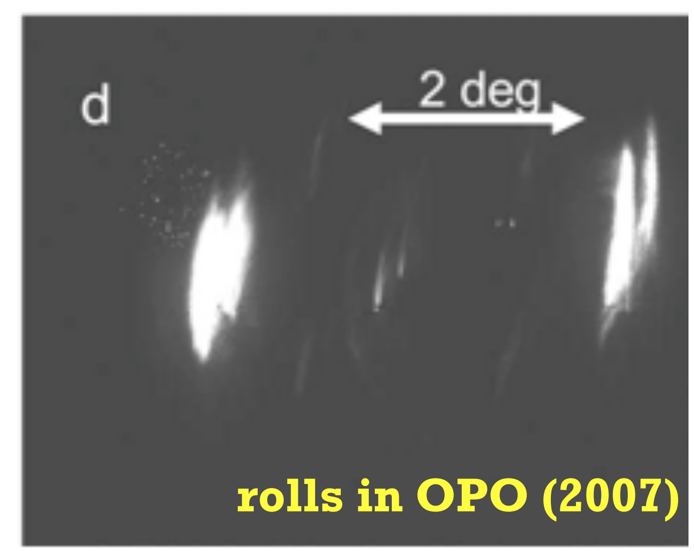
Inst. No Lineal Nice

soliton in semic.(02)

Vilnius University



OPA (?)



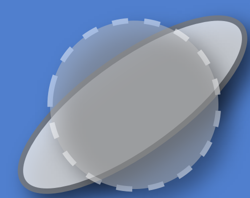
rolls in OPO (2007)

QUANTUM ASPECTS OF OPF

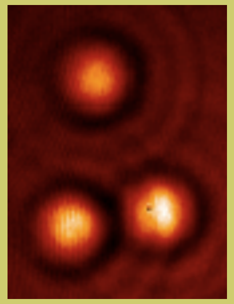
80s from single mode to spatial multimode Quantum Optics. Mainly PDC.

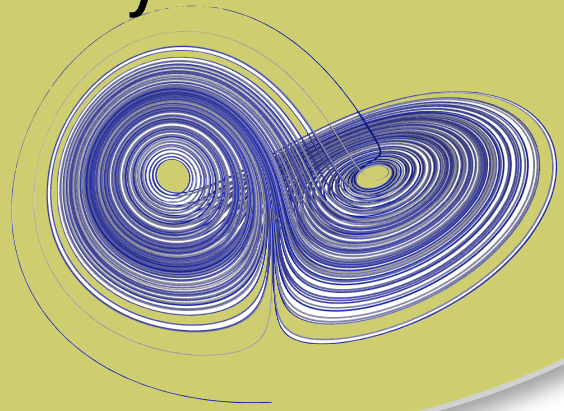
quantum optics

$|HH\rangle + |VV\rangle$



complex systems





VOLUME 68, NUMBER 22 PHYSICAL REVIEW LETTERS 1 JUNE 1992

Quantum Noise Reduction in a Spatial Dissipative Structure

L. A. Lugiato and F. Castelli
Dipartimento di Fisica dell'Università, via Celoria 16, 20133 Milano, Italy
(Received 13 March 1992)

We give the quantum-mechanical formulation of a model which predicts the onset of a spatial dissipative structure in a nonlinear optical system. In the case of roll patterns, we show that the two signal beams which constitute the pattern are correlated twin beams, i.e., their intensity difference exhibits fluctuations below the standard quantum limit.

Applications: Quantum information, quantum imaging and metrology...

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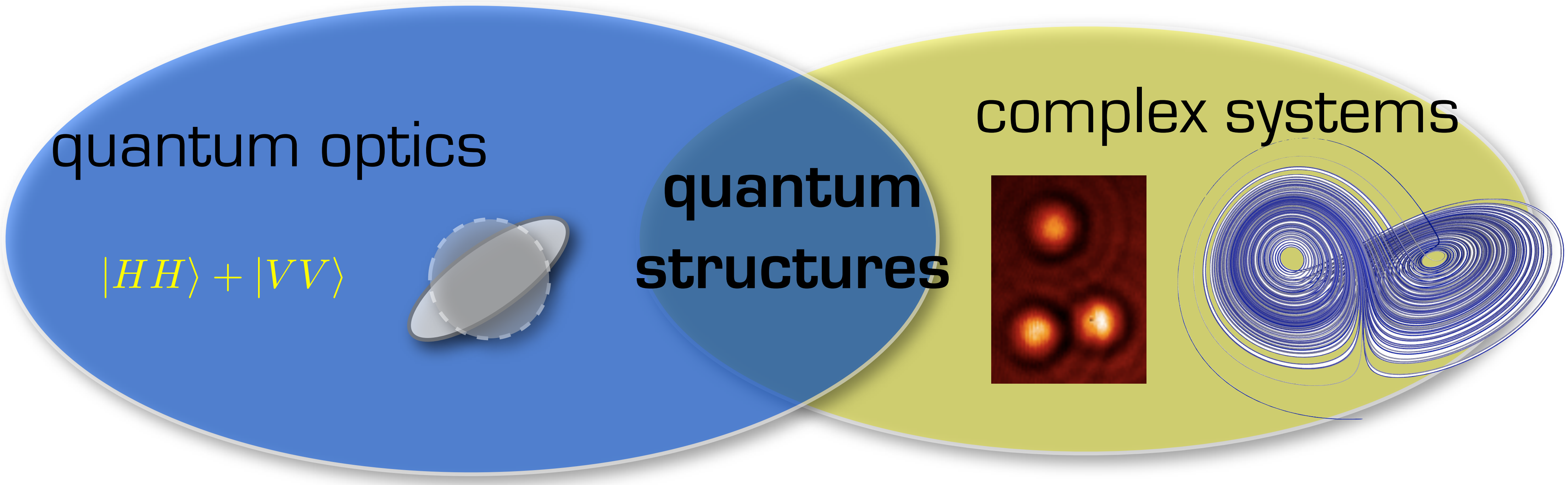

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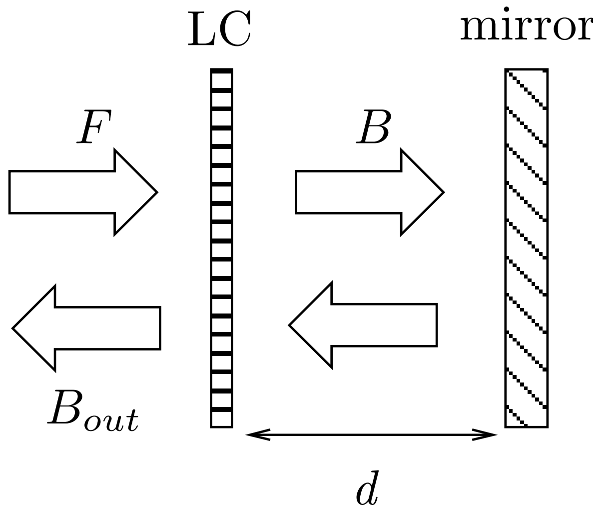
QUANTUM ASPECTS OF OPF

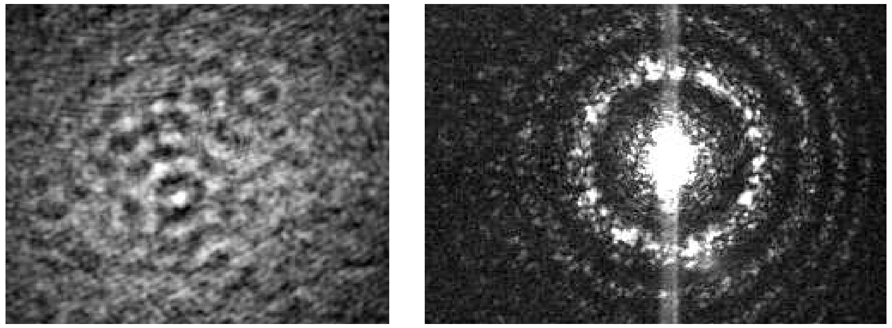
QUANTUM IMAGES

BELOW THRESHOLD

noisy precursors: anticipation of some temporal (w) or spatial (k) characteristics of the state. Less damped modes excited by noise, spontaneous emission.

Jeffries & Weisenfeld ('85)





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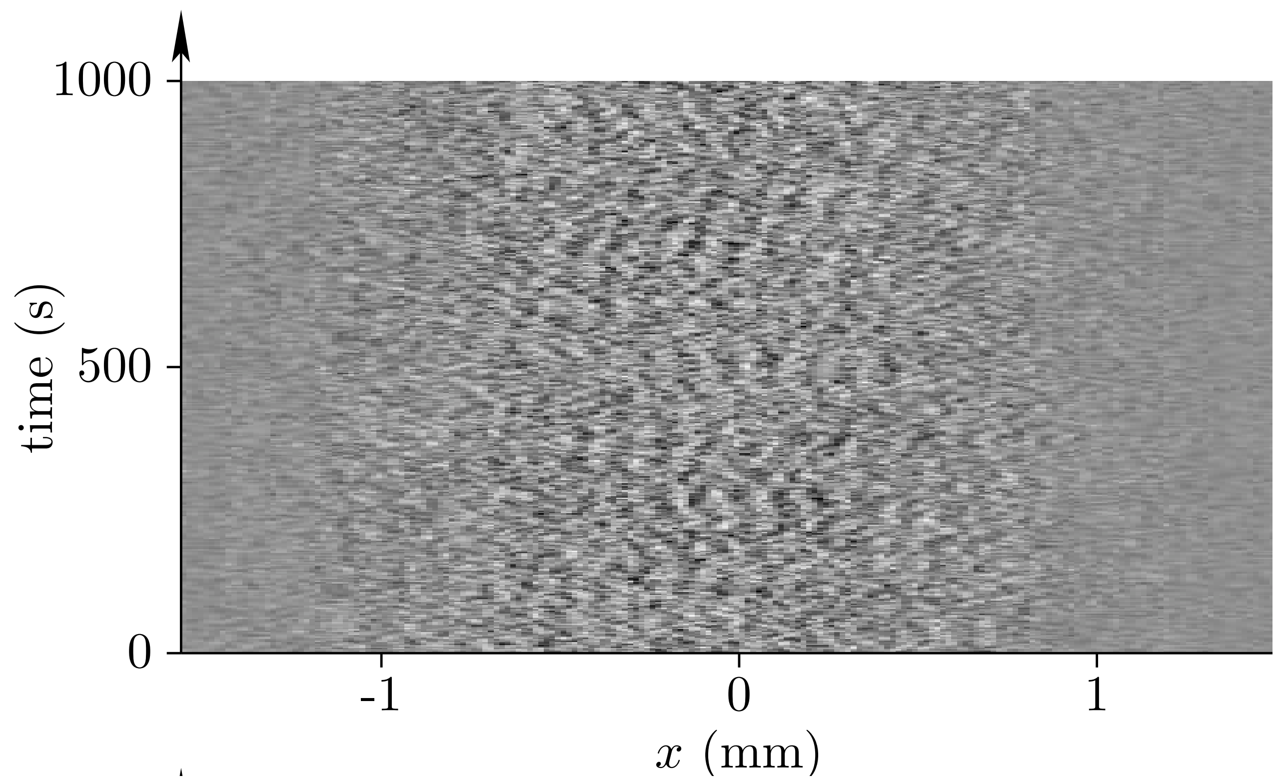

Agez, Louvergneaux, Glorieux & Szwaj (2007)

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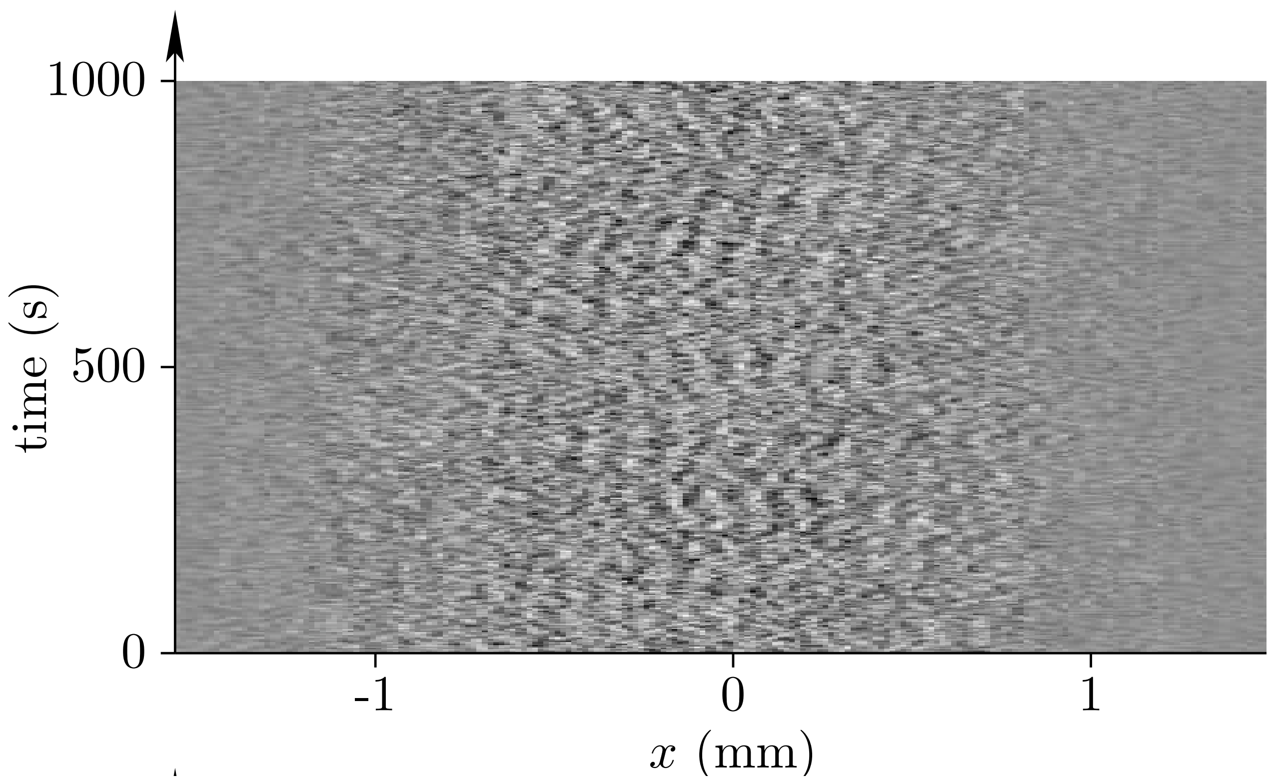
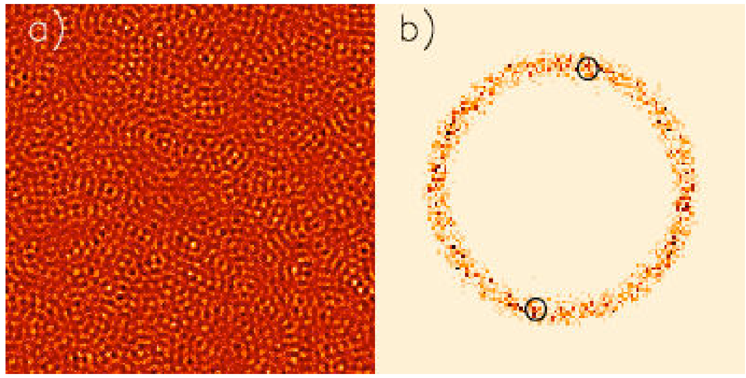


Agez, Louvergneaux, Glorieux & Szwaj (2007)

quantum images: "spatial structures manifested by the correlation functions" between the field at different points, and also by the "very noisy images" of the spatial fluctuations

Lugiato & al. (96).



twin photons

QUANTUM ASPECTS OF OPF

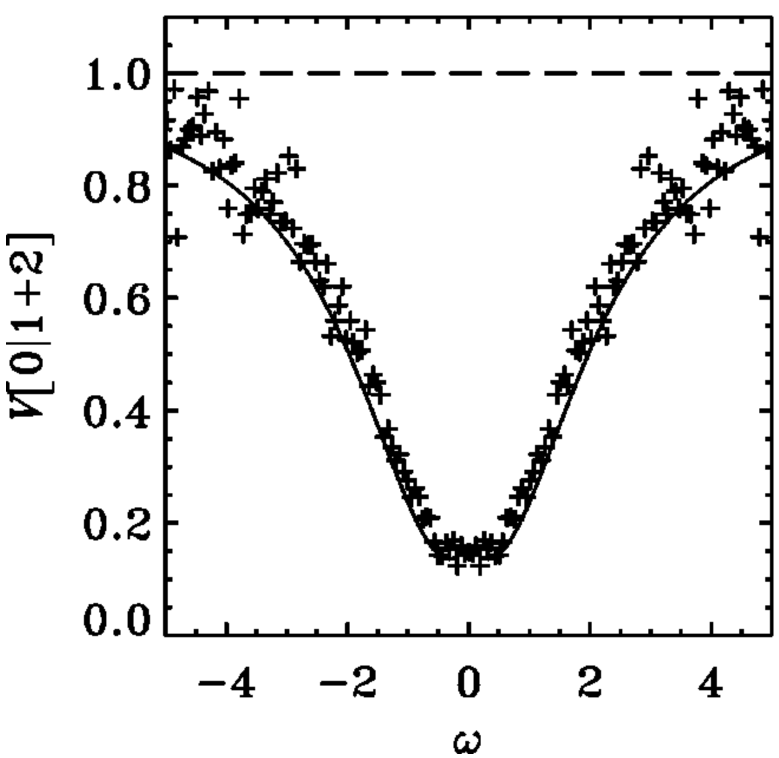
QUANTUM IMAGES

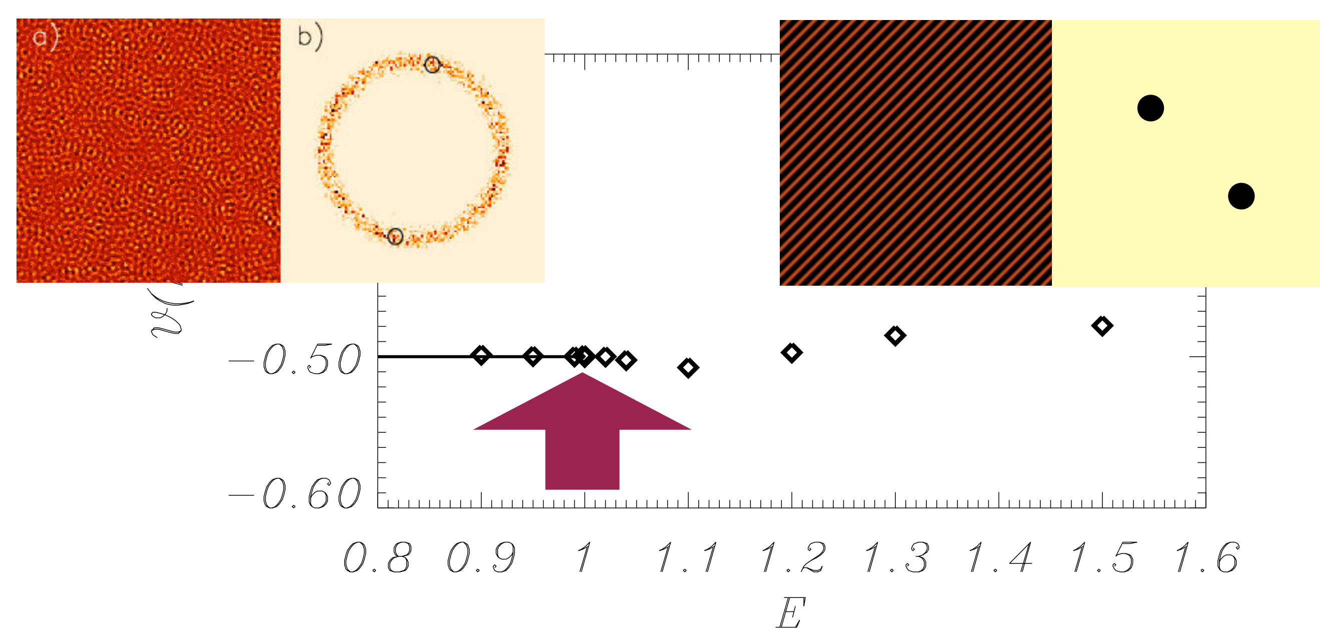
below threshold: twin beams,
2 mode squeezed vacuum...

INTENSE FIELDS

above threshold
'macroscopically' populated spatial modes.
Quantum effects?

$$\mathcal{V}(k) = \frac{\langle : [\delta \hat{N}_1(k) - \delta \hat{N}_1(-k)]^2 : \rangle}{\mathcal{N}_N(k)}$$





... in stationary patterns

Lugiato & Grynberg ('95), Hoyuelos et al. ('99), Zambrini et al., (2001)

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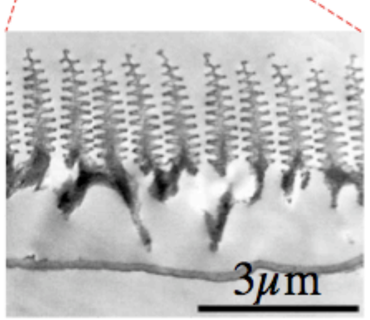
PHOTONIC CRYSTALS

movement of e⁻ in a semiconductor	light in a photonic crystal
PERIODICITY of CRYSTAL: BAND-GAP for e-	PERIODICITY of n: BAND-GAP for photons

Photonic Crystals in Nature

Morpho rhetenor butterfly

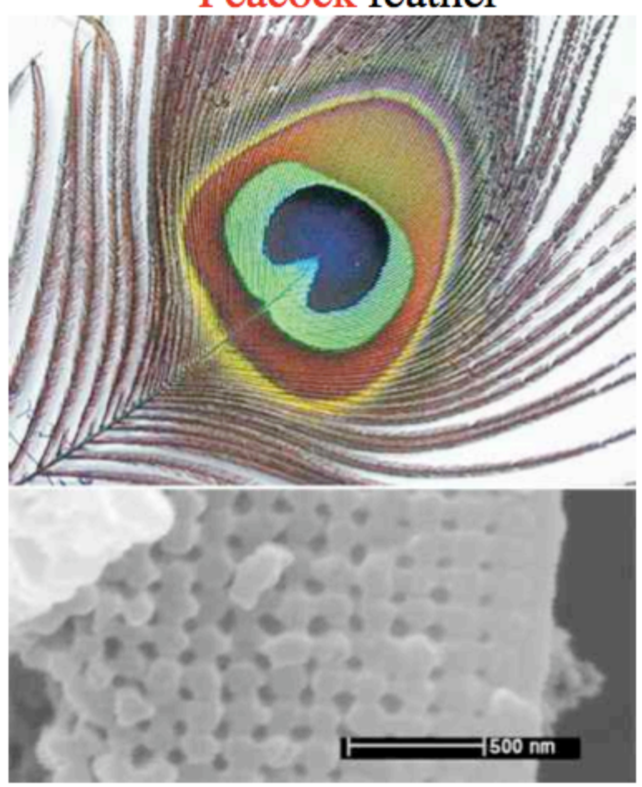
wing scale:



[P. Vukosic *et al.*, *Proc. Roy. Soc: Bio. Sci.* **266**, 1403 (1999)]

[also: B. Gralak *et al.*, *Opt. Express* **9**, 567 (2001)]

Peacock feather

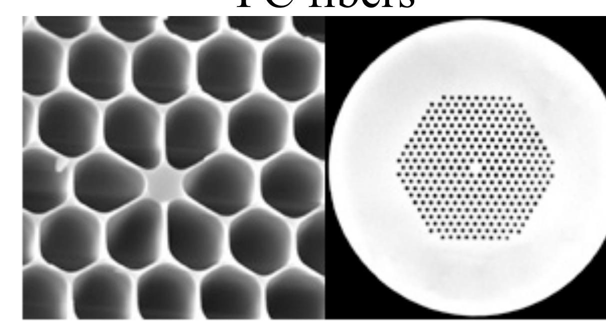


[J. Zi *et al*, *Proc. Nat. Acad. Sci. USA*, **100**, 12576 (2003)]
[figs: Blau, *Physics Today* **57**, 18 (2004)]

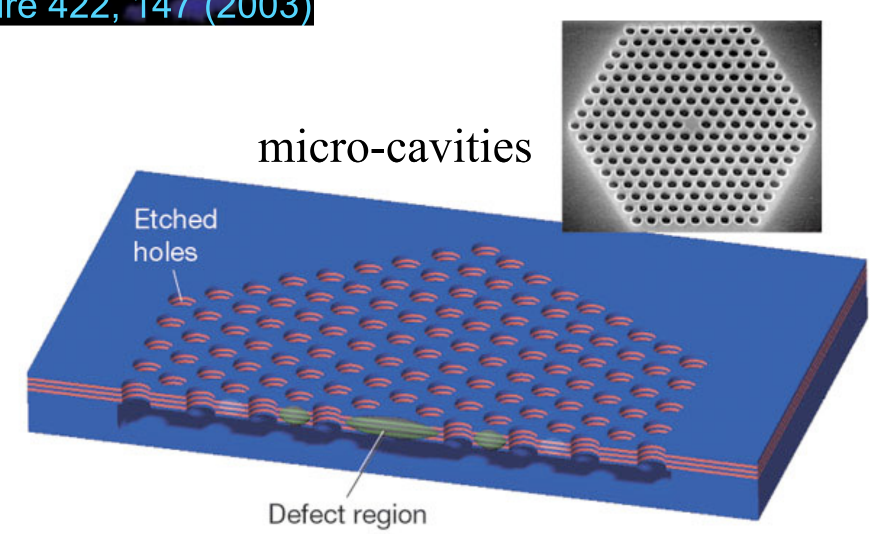
http://ab-initio.mit.edu/index.html

Control of Light

PC fibers



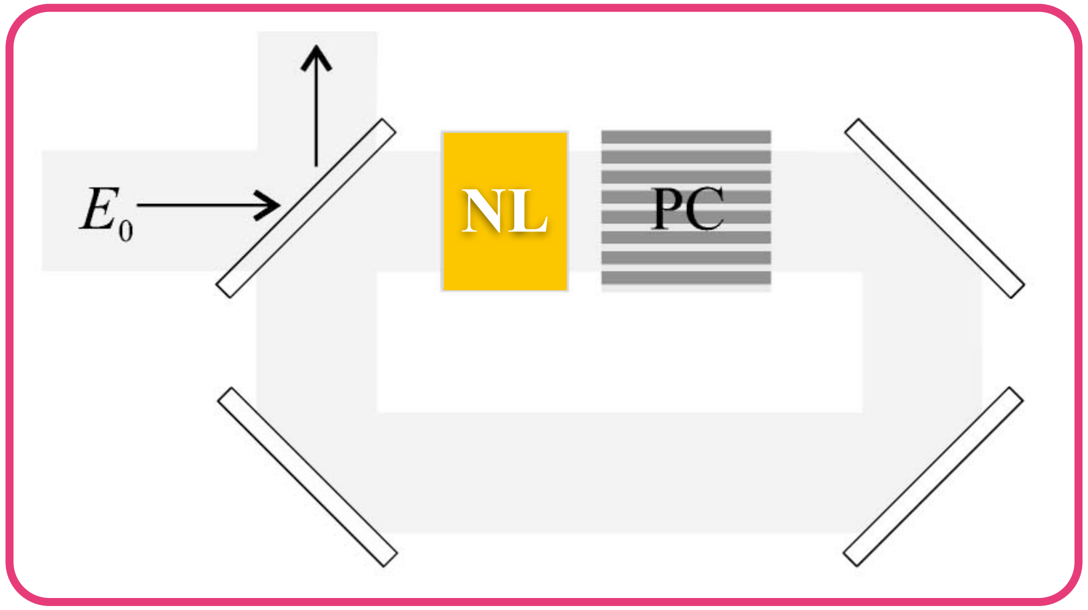
micro-cavities

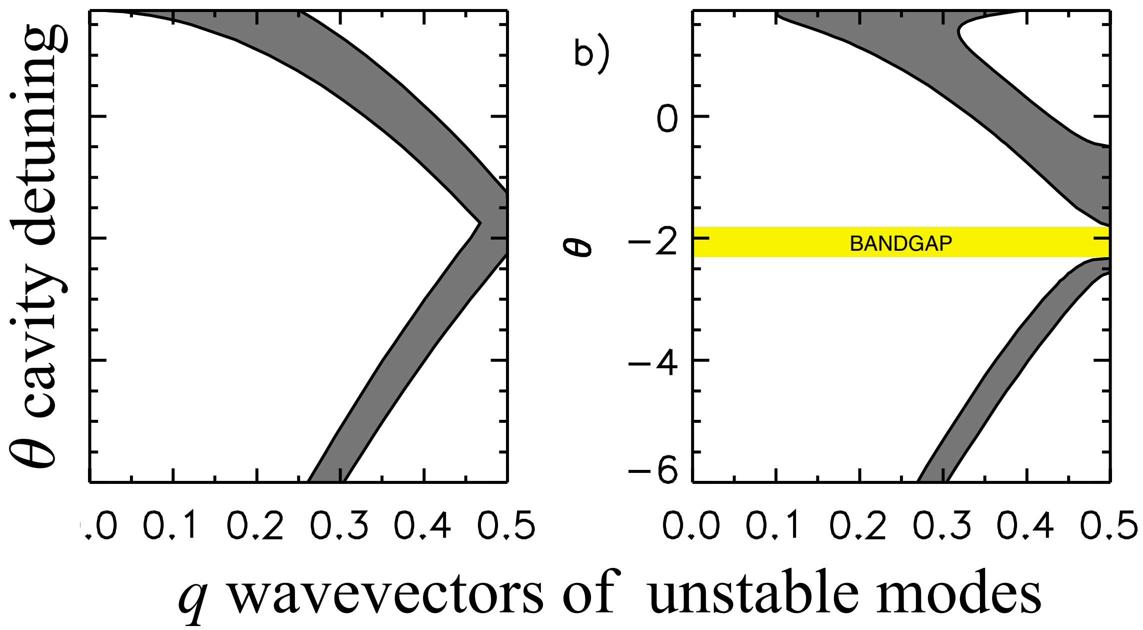


Nature 424, 839 (2003)

Photonic Band-Gap Inhibition of Modulational Instabilities

Damià Gomila, Roberta Zambrini, and Gian-Luca Oppo
Department of Physics, University of Strathclyde, 107 Rottenrow East, Glasgow, G4 0NG, United Kingdom





Gomila, Zambrini, Oppo, PRL **92**, 253904 (2004)

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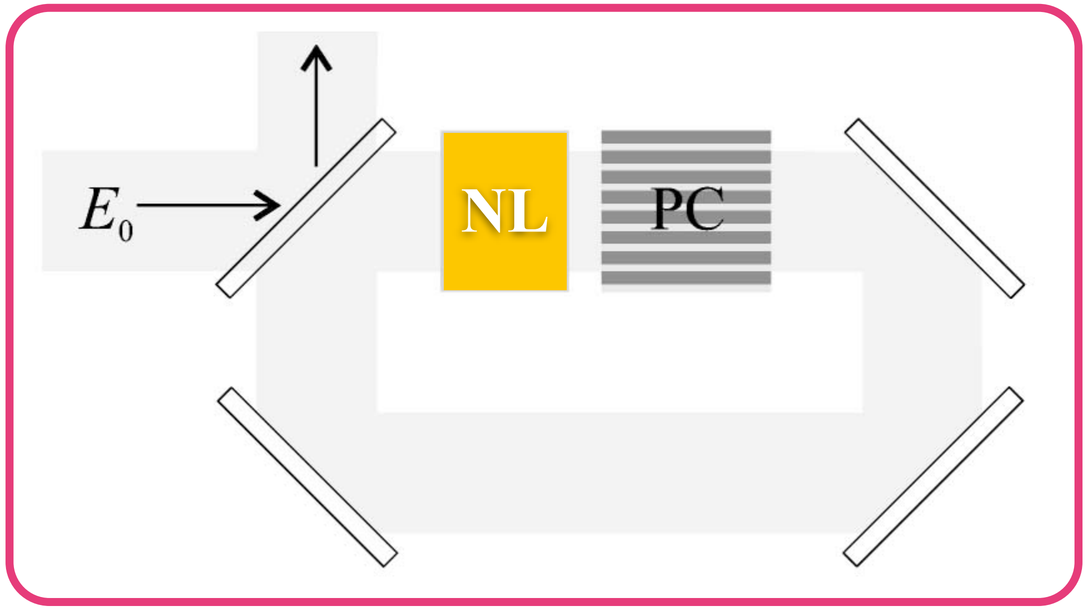
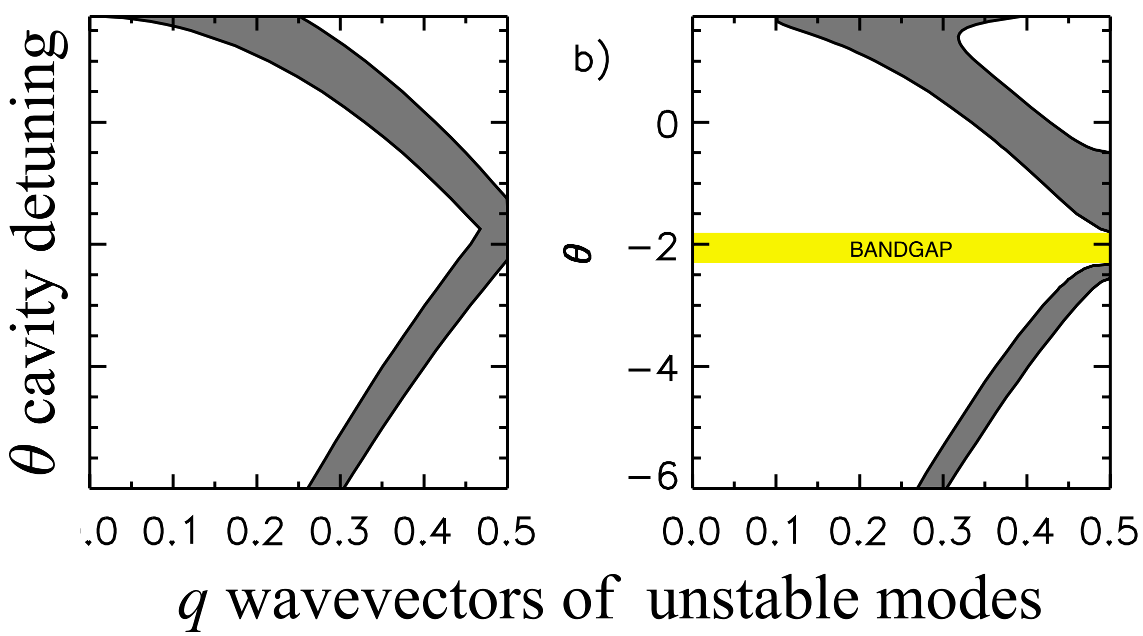
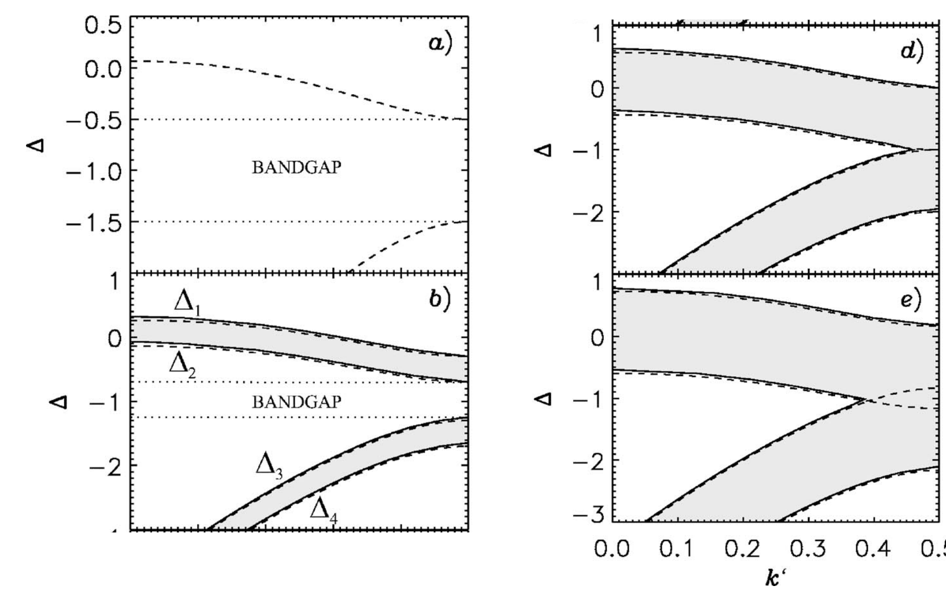
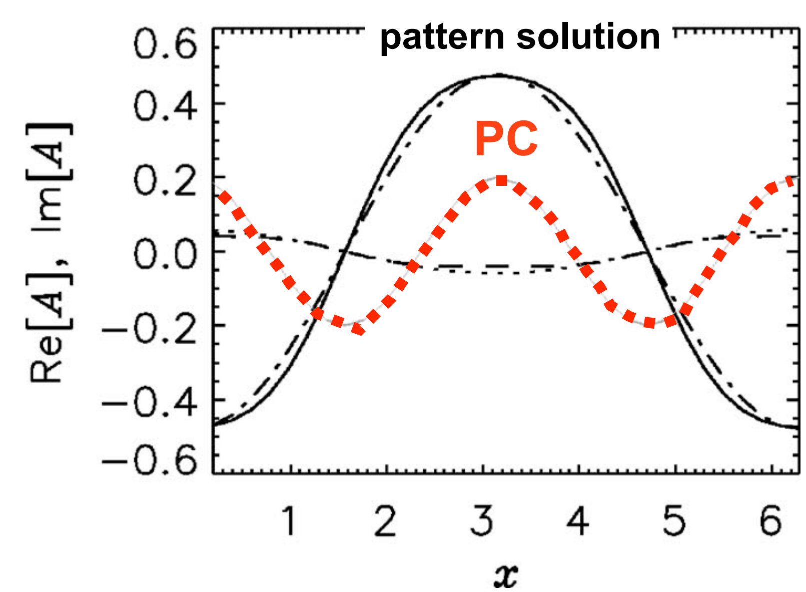




Gomila, Zambrini, Oppo, PRL **92**, 253904 (2004)

Analytical calculations for SROPO





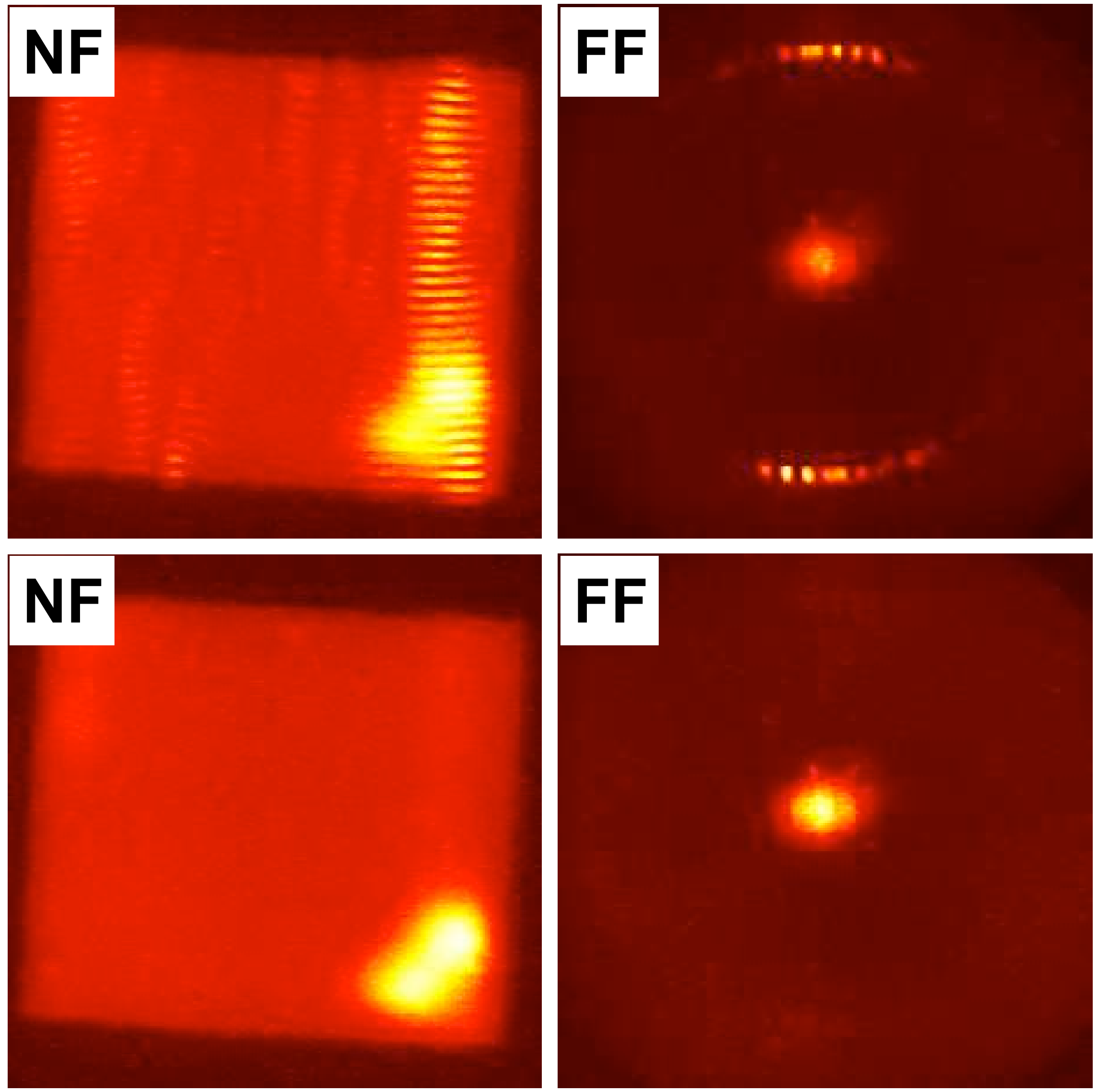
Gomila, Oppo, PRE **72**, 016614 (2005)

Experiment on PC inhibition of MI

Control of broad-area vertical-cavity surface emitting laser emission
by optically induced photonic crystals

no PC

with PC



Terhalle, Radwell, Rose, Denz, and Ackemann, submitted

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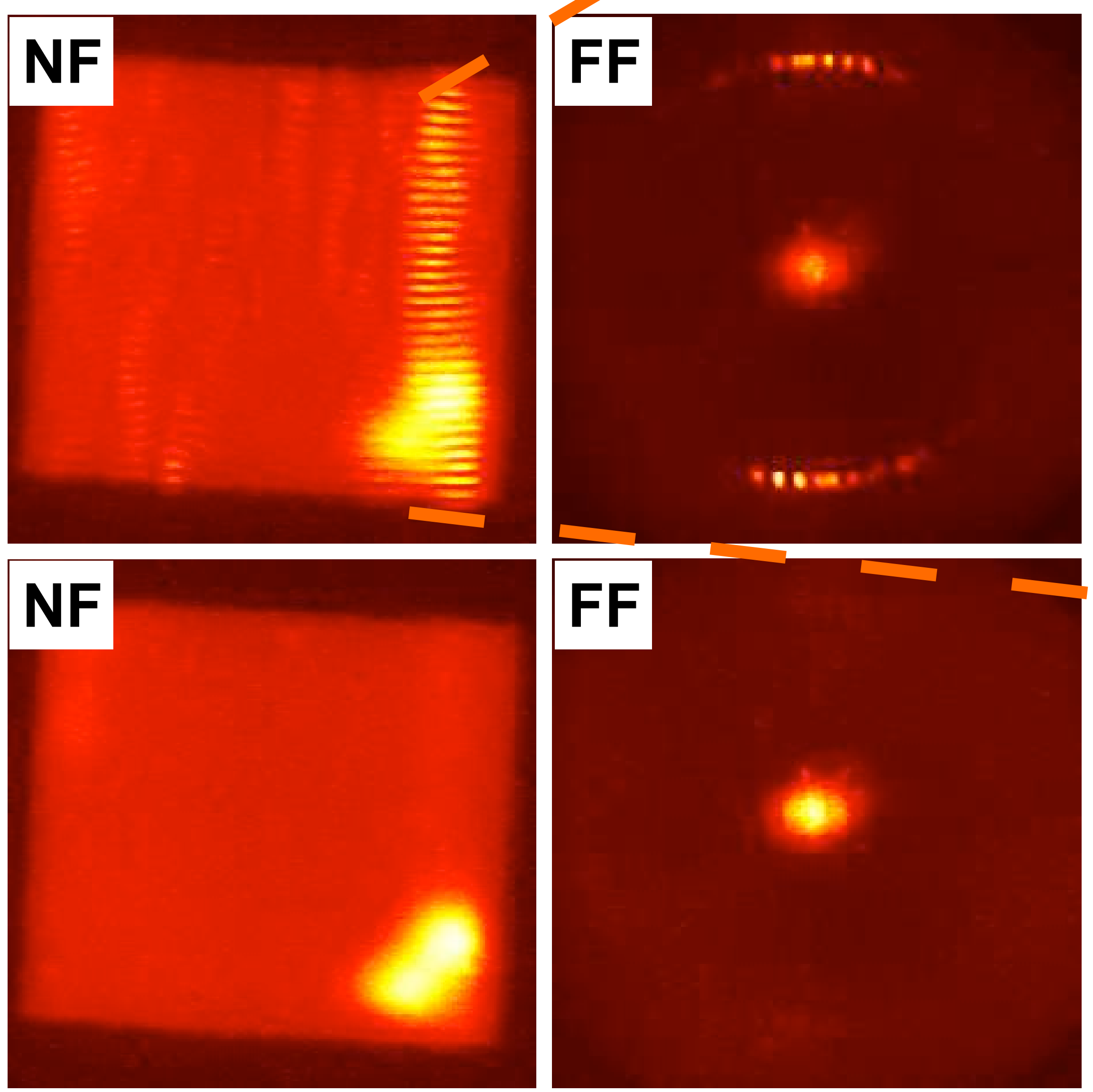

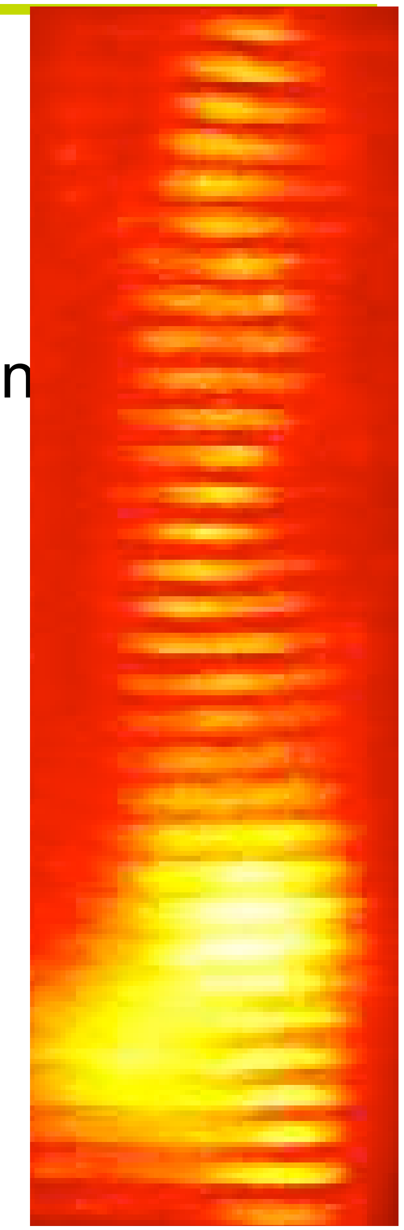

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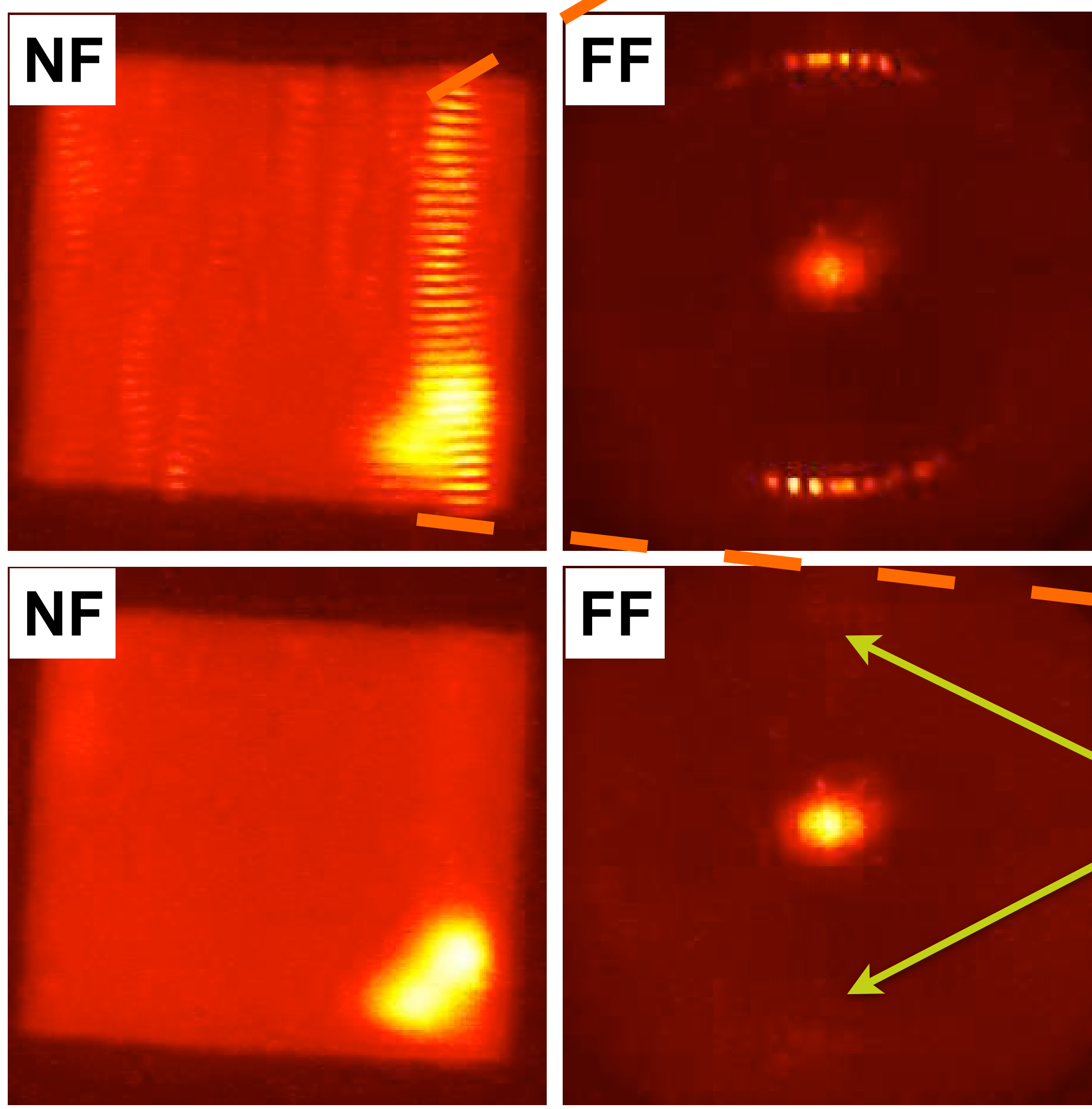

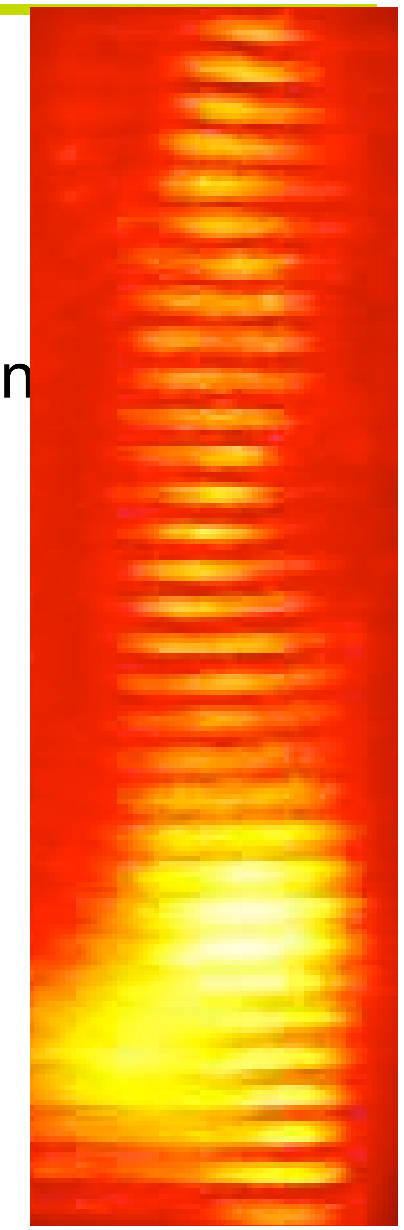

no pattern

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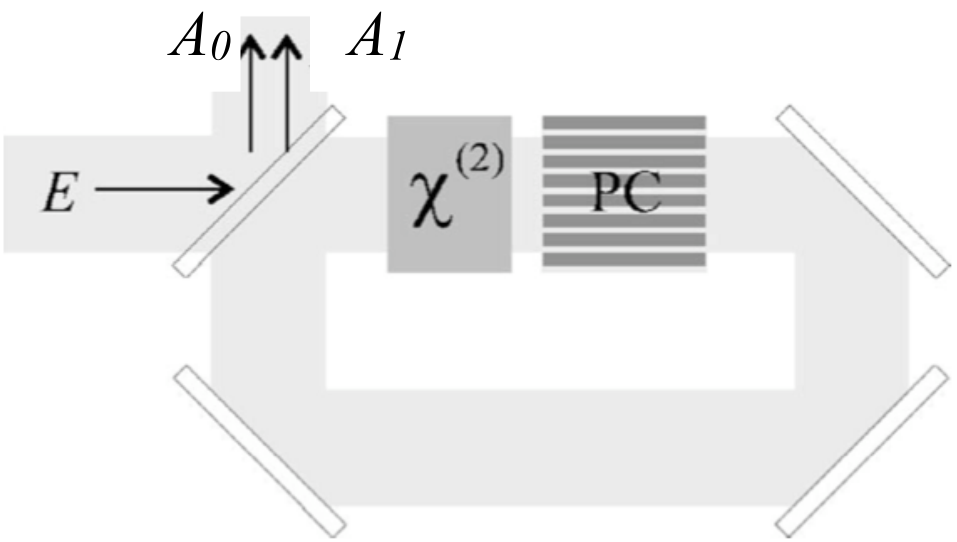
Model: type I degenerate OPO with PC

NONLINEAR PHOTONS INTERACTIONS: methodological challenge



$$Q(\alpha_0,\alpha_1) = \frac{1}{\pi}\langle \alpha_0,\alpha_1|\hat{\rho}|\alpha_0,\alpha_1\rangle$$

$$\frac{\partial\hat{\rho}}{\partial t} = \frac{1}{i\hbar}[\hat{H},\hat{\rho}] + \hat{\Lambda}\hat{\rho}$$

Fokker-Planck equation*

Yuen & Tombesi, Opt. Commun. **59**, 155 (1986)
Zambrini & Barnett PRA **65**, 053810 (2002)

$$\partial_t\alpha_0(\vec{x},t) = -\left[(1+i(\Delta_0+I_0\sin k_p x) - i\nabla^2\right]\alpha_0(\vec{x},t) + E - \frac{1}{2}\alpha_1^2(\vec{x},t) + \sqrt{\frac{2}{a}\frac{g}{\gamma}}\xi_0(\vec{x},t)$$

$$\partial_t\alpha_1(\vec{x},t) = -\left[(1+i(\Delta_1+I_1\sin k_p x) - 2i\nabla^2\right]\alpha_1(\vec{x},t) + \alpha_0(\vec{x},t)\alpha_1^*(\vec{x},t) + \sqrt{\frac{2}{a}\frac{g}{\gamma}}\xi_1(\vec{x},t)$$

$k_p \sim k_c$

Zambrini, Barnett, Colet, San Miguel, EPJD **22**, 461 (2003)

Model: type I degenerate OPO with PC

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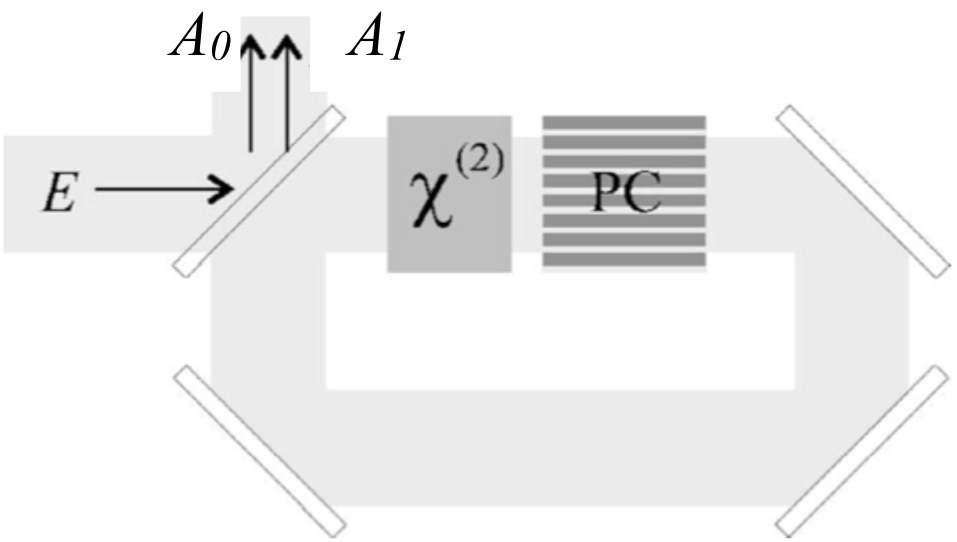

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pump

losses — cavity detunings — PC — diffraction — quadratic NL

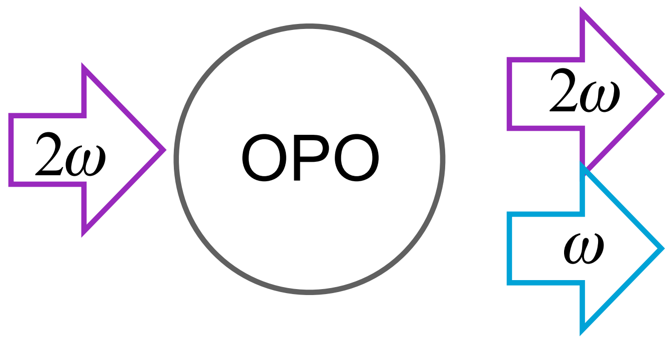
$k_p \sim k_c$

MULTIPLICATIVE WHITE NOISE

Zambrini, Barnett, Colet, San Miguel, EPJD **22**, 461 (2003)

OUTLINE

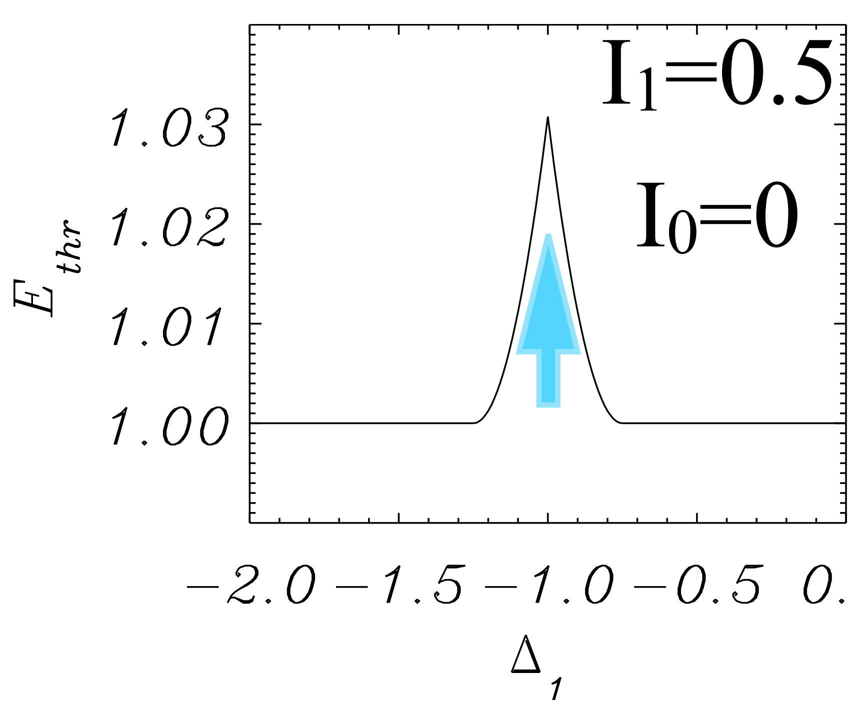
PARAMETRIC THRESHOLD



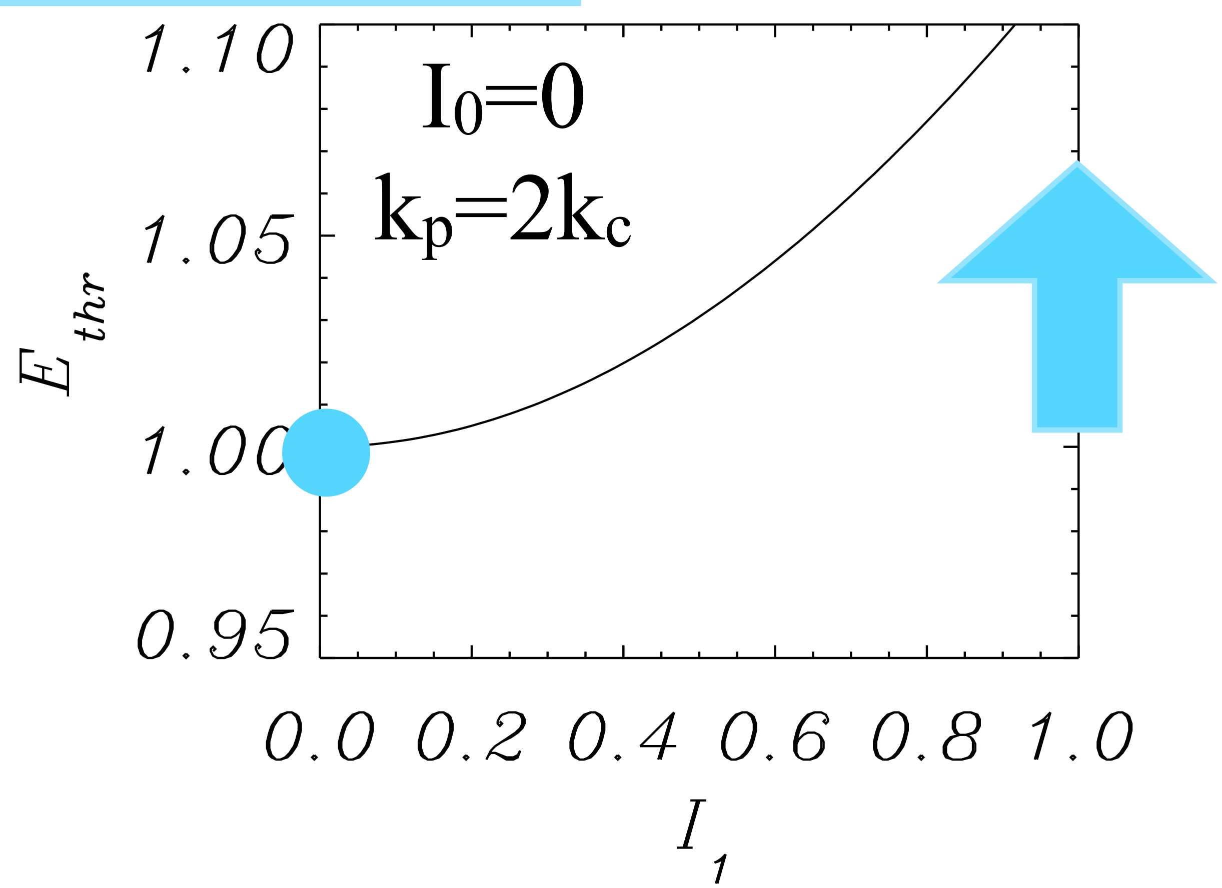
Threshold of emission of intense field at ω

$$E_c = \sqrt{1+\Delta_0^2}$$

threshold inhibition -FOR DOWN CONVERSION & MI-

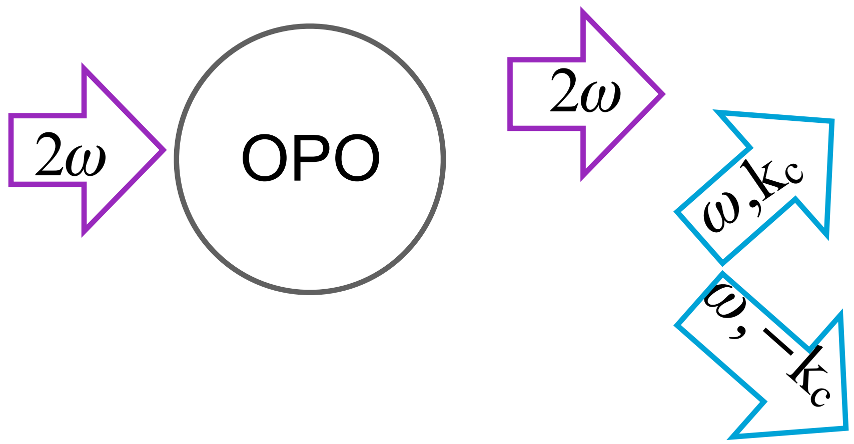


maximum at $k_p=2k_c$



Gomila, Oppo, PRE **72**, 016614 (2005)

PARAMETRIC THRESHOLD

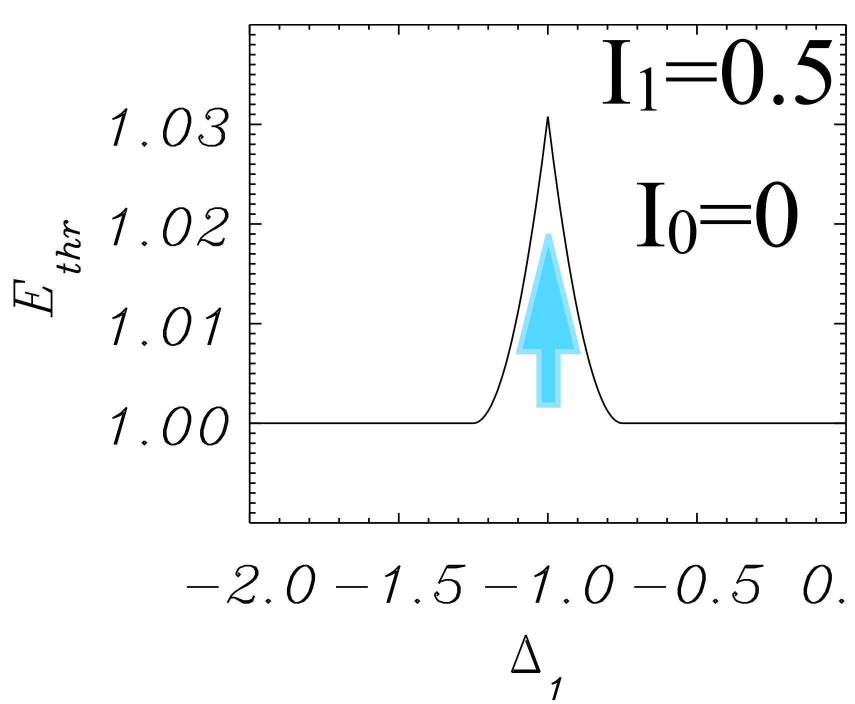


Threshold of emission of intense field at ω

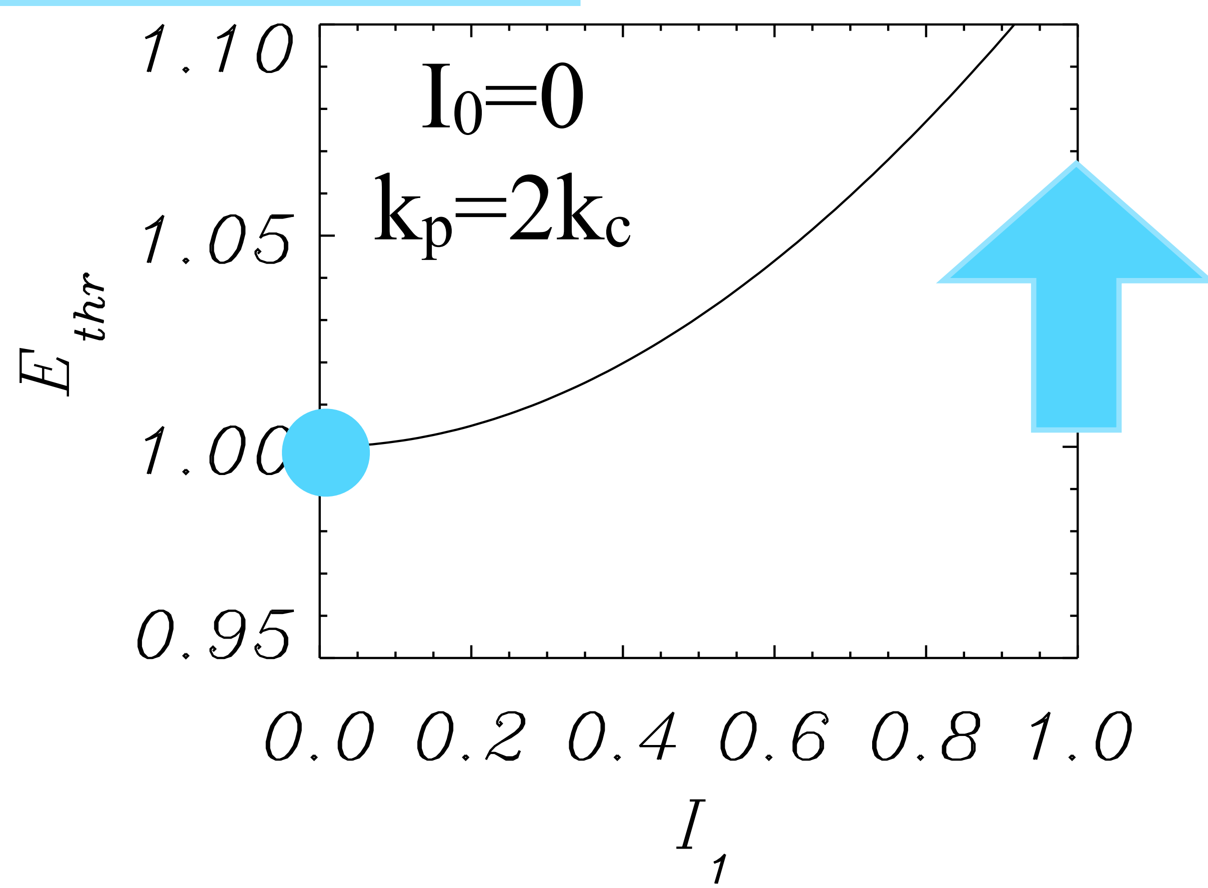
$$E_c = \sqrt{1 + \Delta_0^2}$$

for negative signal detuning → emission of tilted waves

threshold inhibition -FOR DOWN CONVERSION & MI-



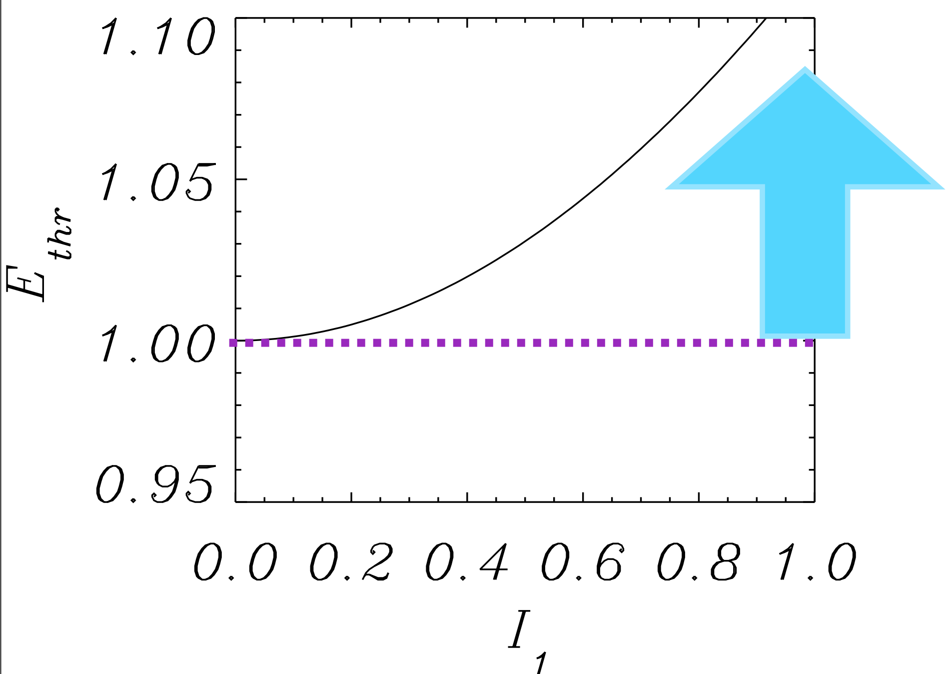
maximum at $k_p=2k_c$



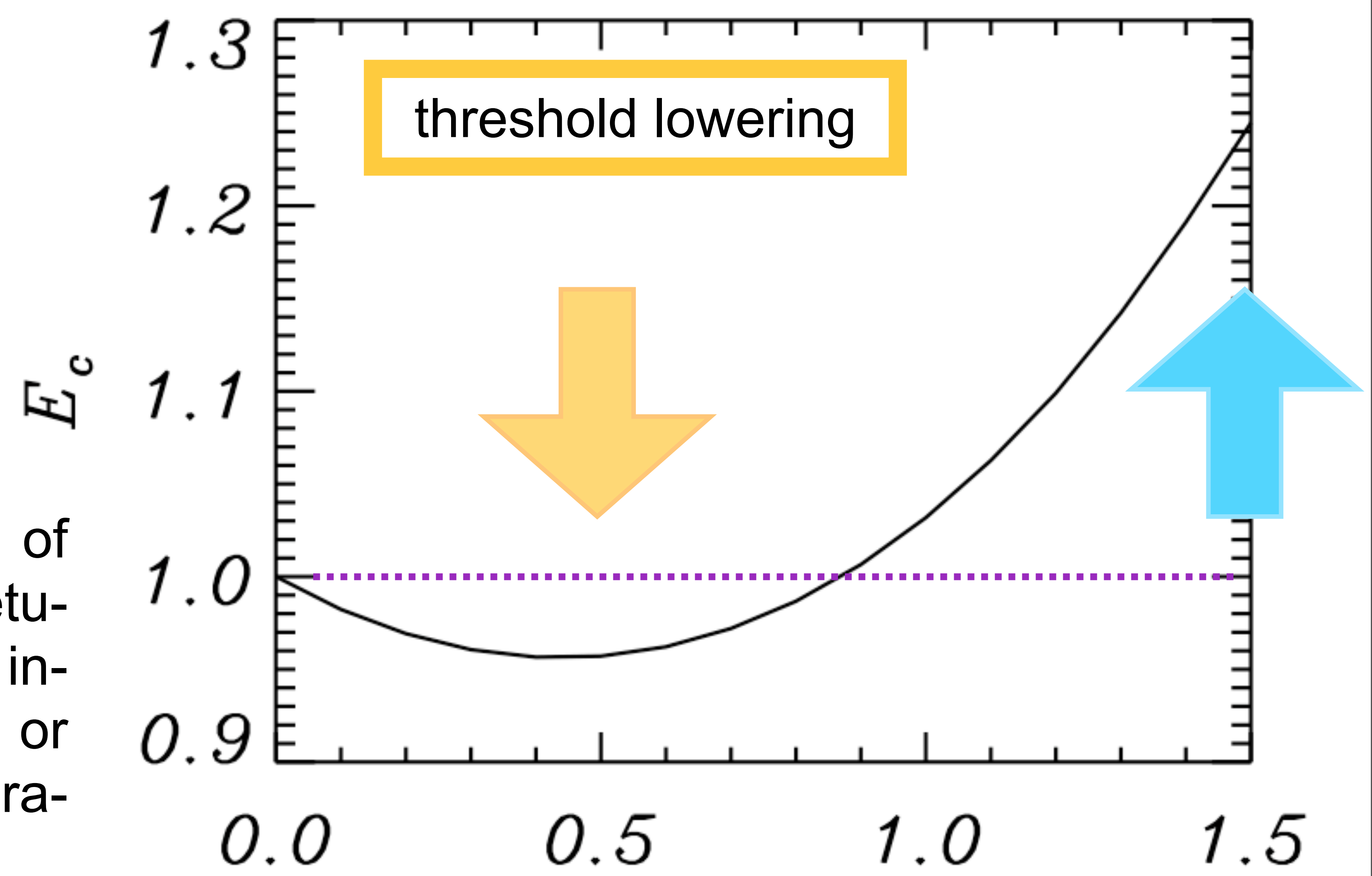
Gomila, Oppo, PRE **72**, 016614 (2005)

PARAMETRIC THRESHOLD

$I_0=0,\ k_p=2k_c$



$I_0=I_1,\ k_p=2k_c$

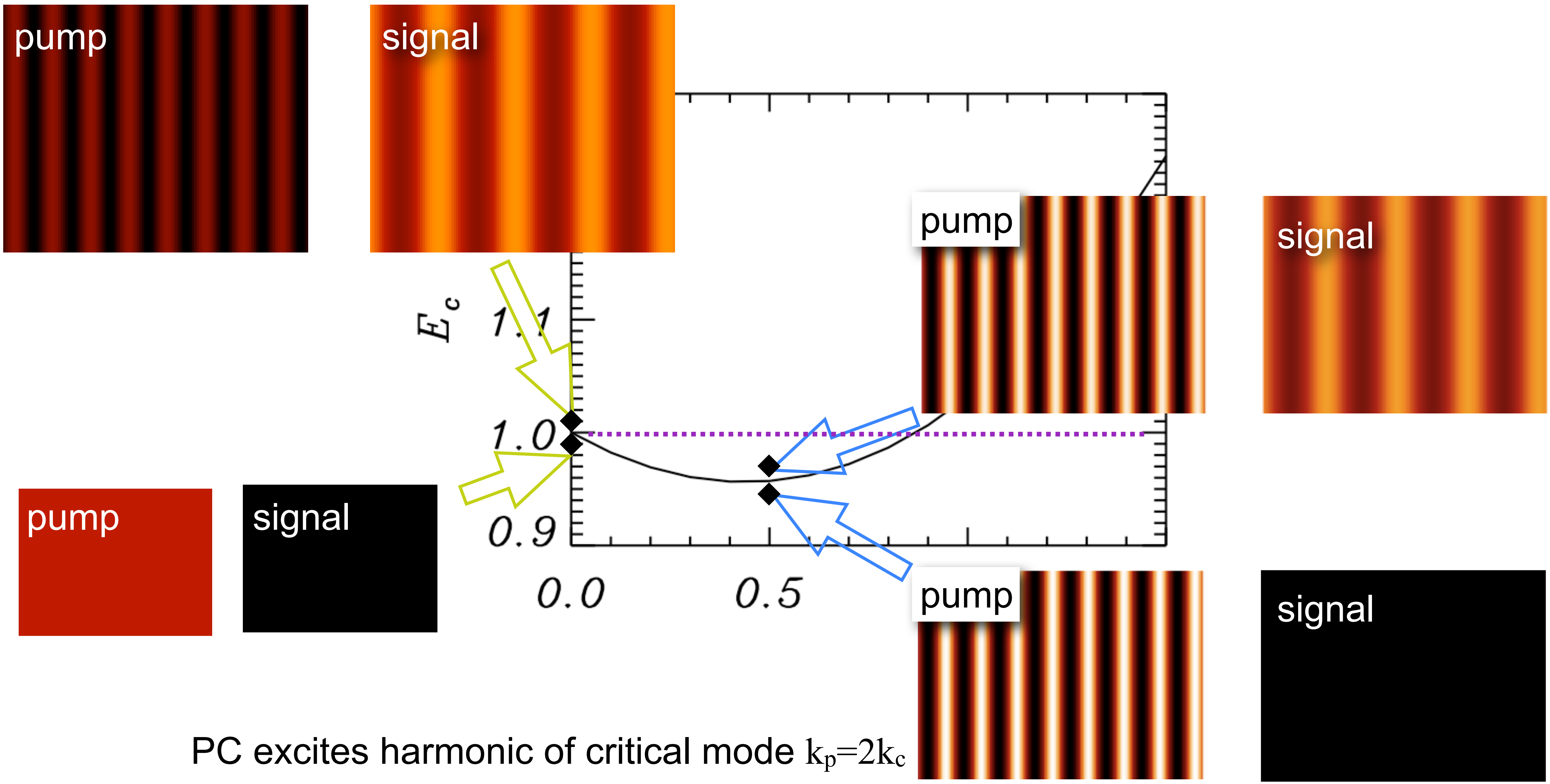


depending on the relative amplitude of modulation in pump and signal detunings, the threshold value can be increased (**inhibition** of the instability) or decreased (**enhancement** of the parametric effect for a given E).

why? PC excites harmonic of critical mode $k_p=2k_c$....

pump profile and signal pattern

CASE: $I_0 = I_1$, $k_p = 2k_c$



PC excites harmonic of critical mode $k_p = 2k_c$

OUTLINE

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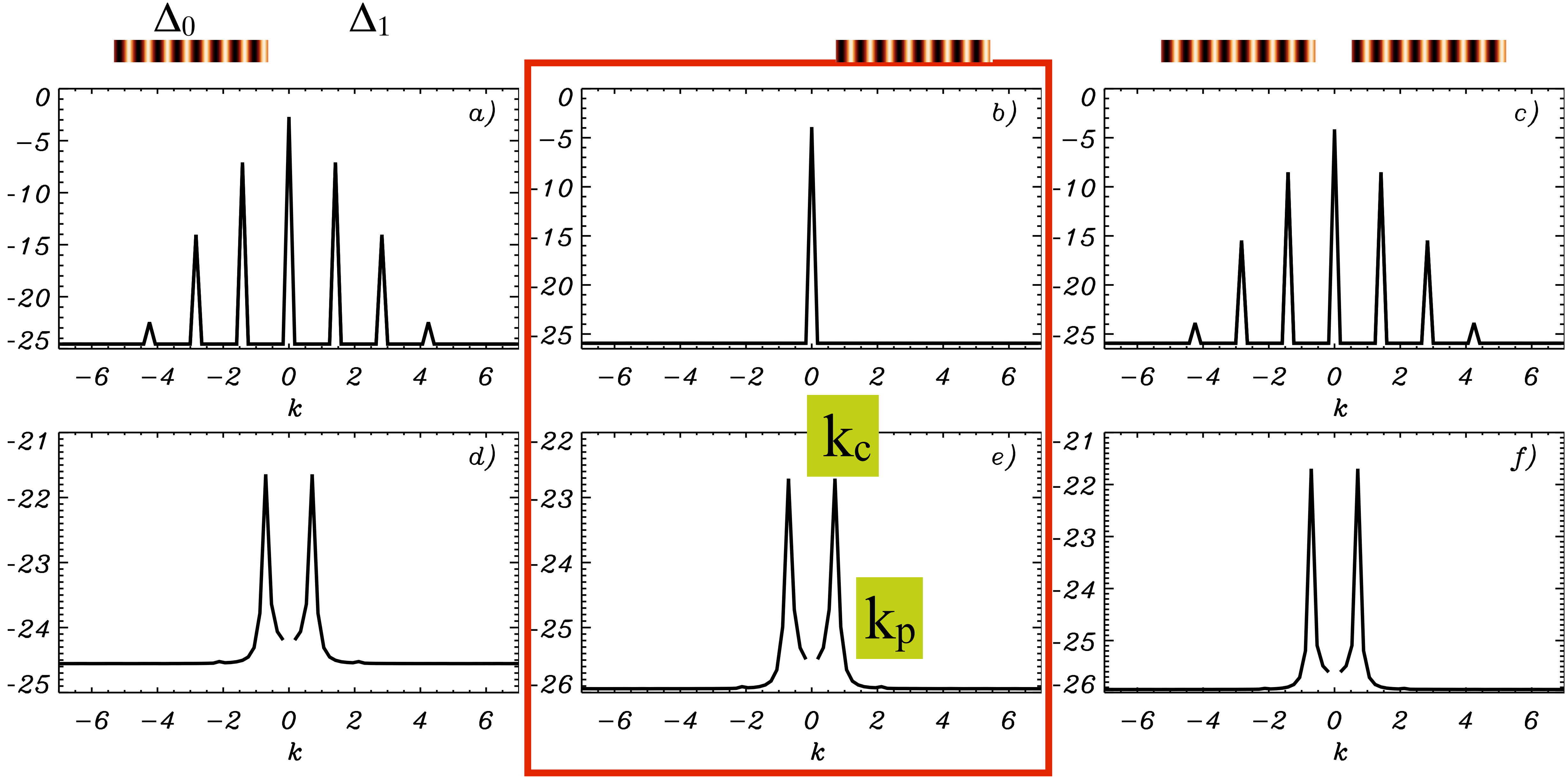
1% BELOW THRESHOLD: QUANTUM IMAGES

$k_p=2k_c$

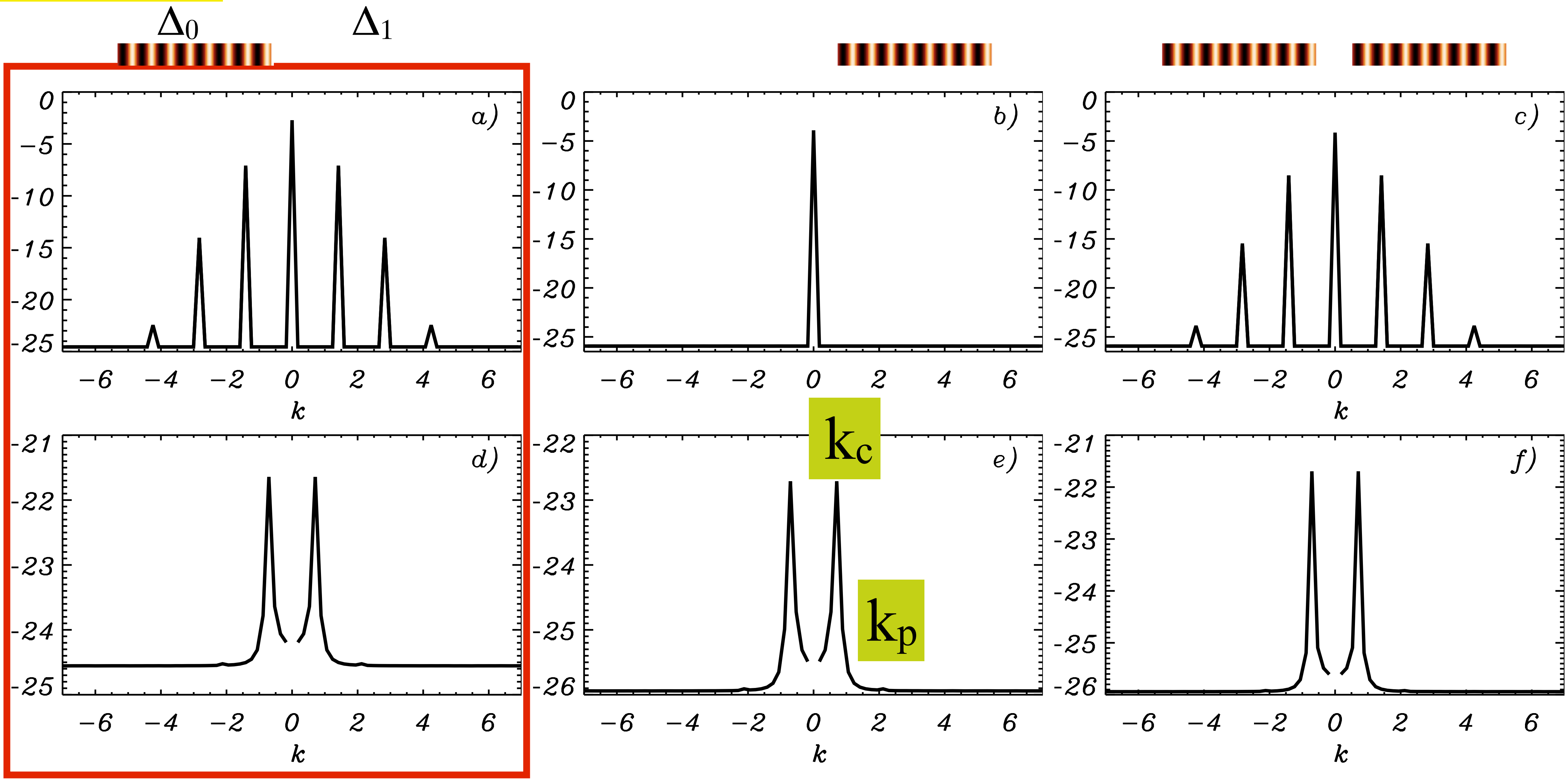
average far field intensity



1% BELOW THRESHOLD: QUANTUM IMAGES

$k_p = 2k_c$

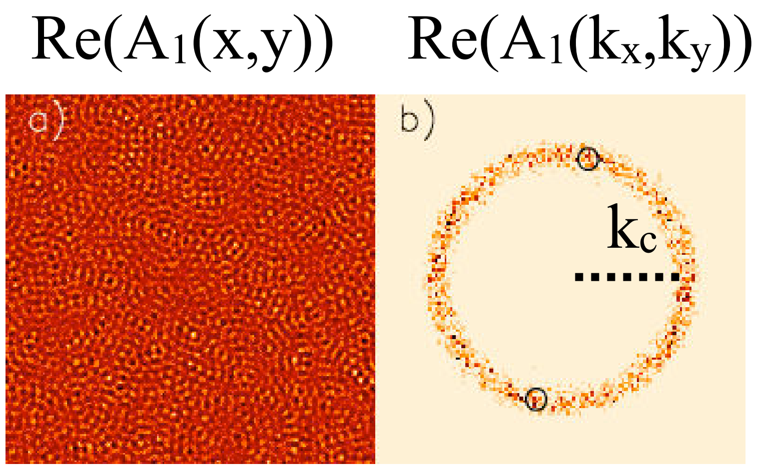
average far field intensity

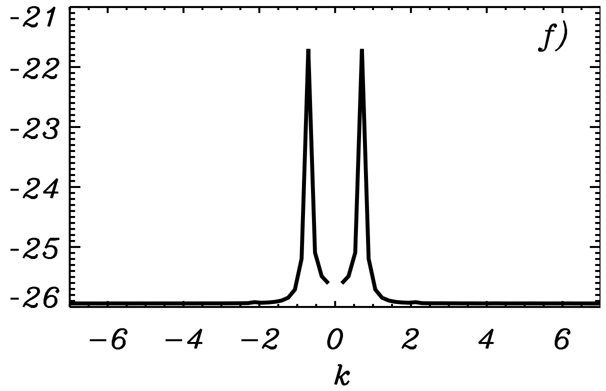


QUANTUM IMAGES WITH HARMONICS

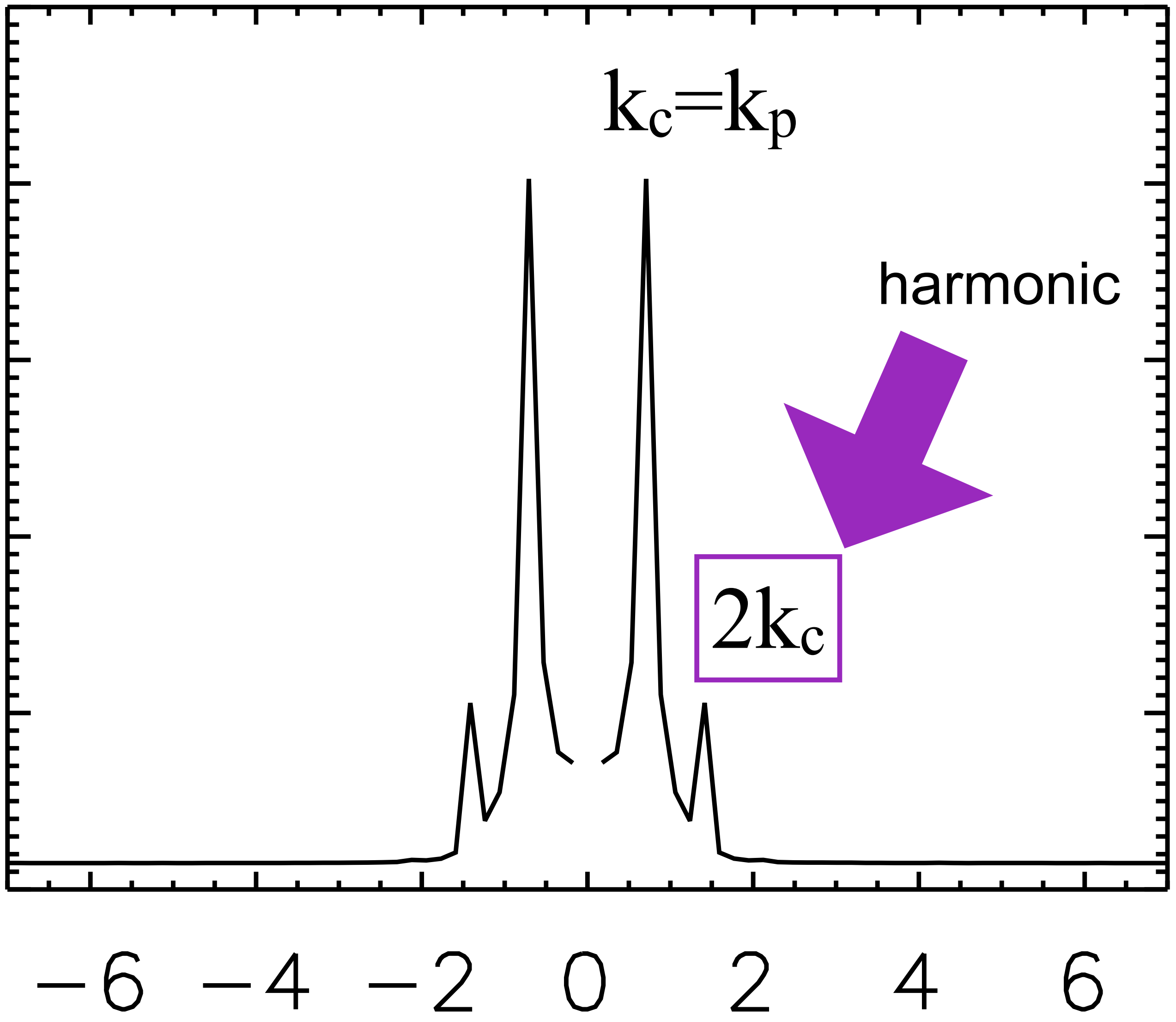
changing PC periodicity from $k_p=2k_c$ to $k_p=k_c$

PC changes the spatial distribution of the spontaneous emission

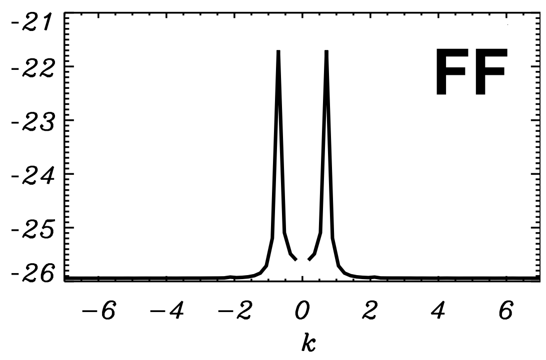




multimode noisy precursors

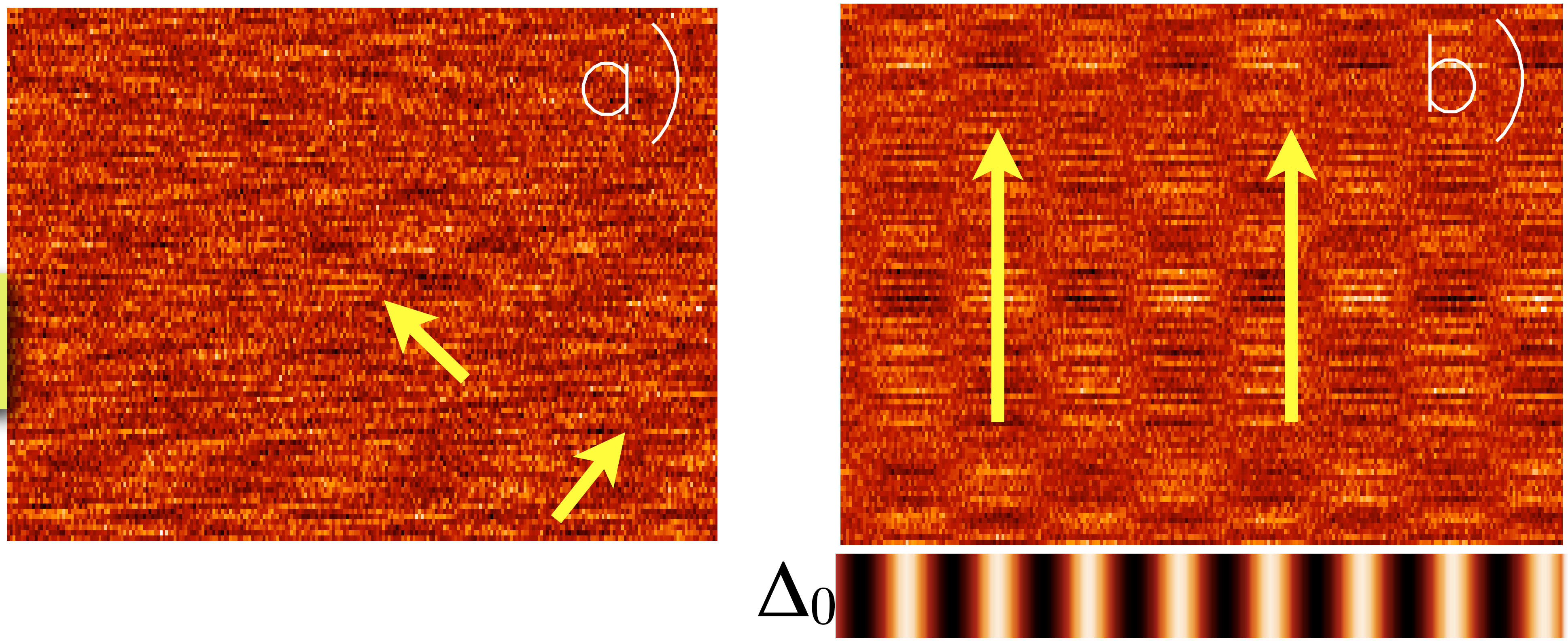


BELOW THRESHOLD: QUANTUM IMAGES



NF quantum fluctuations in real part of signal 1% below threshold

undamped fluctuations at kc, **phase diffusion**



no PC or I_1

PC ⟶ TRANSLATIONAL SYMMETRY BREAKING

undamped fluctuations in locked modes below threshold

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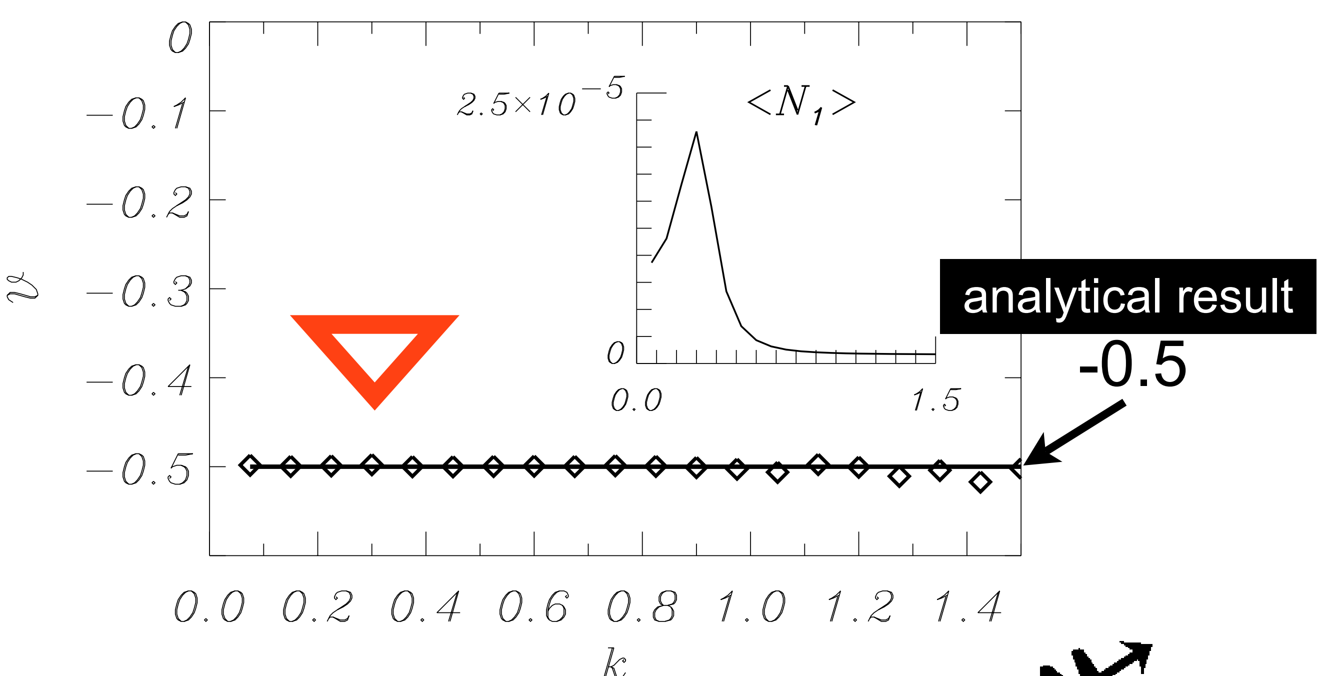
TWIN BEAMS CORRELATIONS

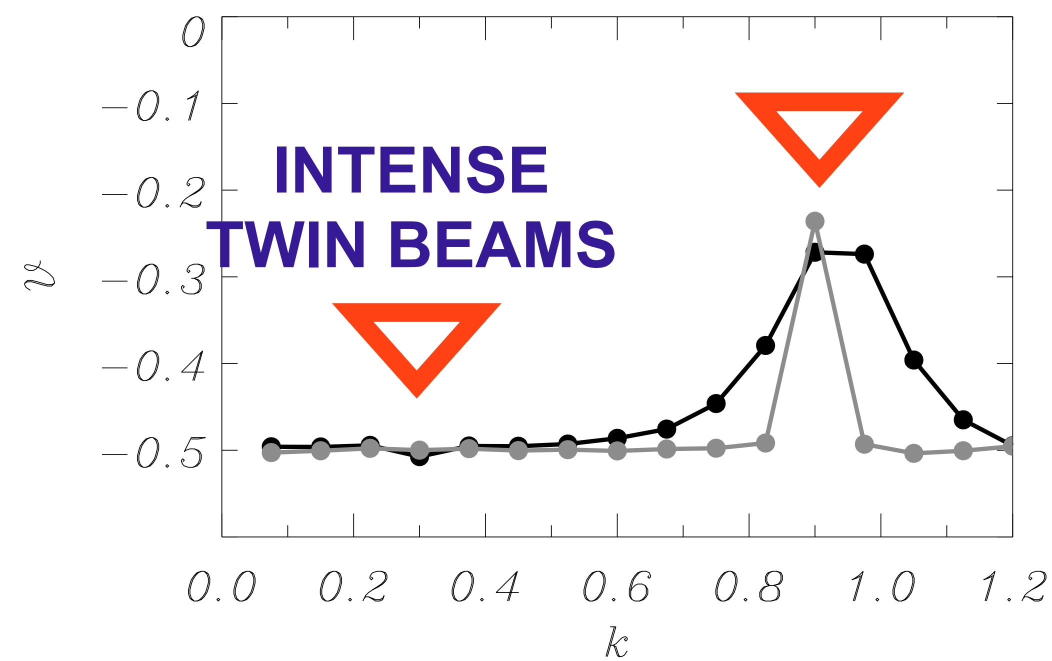
OPO <u>without</u> PC

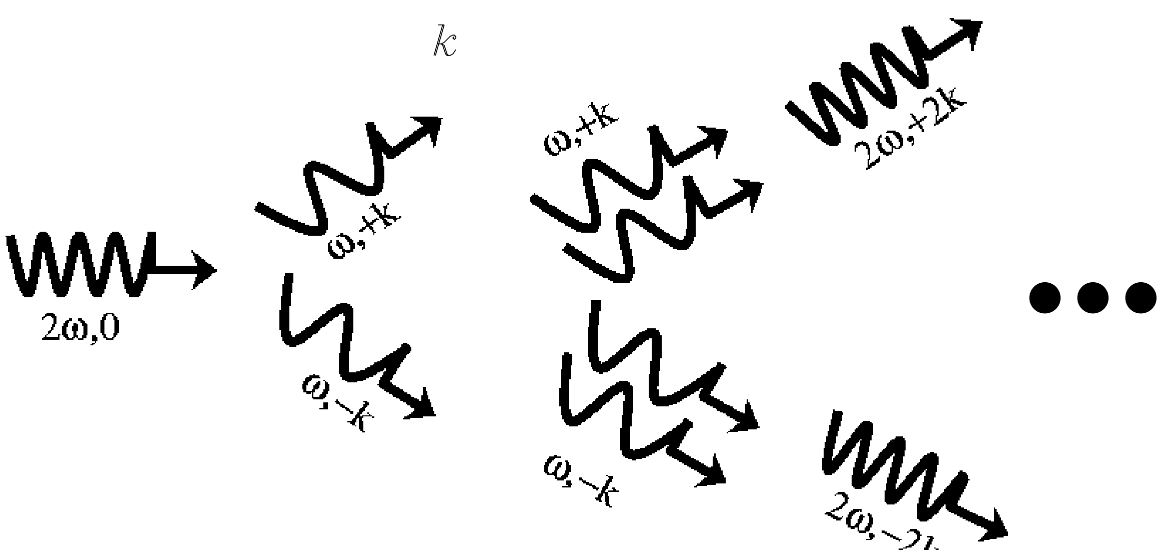
$$\mathcal{V}(k) = \frac{\langle : [\delta \hat{N}_1(k) - \delta \hat{N}_1(-k)]^2 : \rangle}{\mathcal{N}_N(k)}$$

below threshold



above threshold





PRESERVED TWIN BEAMS CORRELATIONS IN INTENSE MODES

<u>SECONDARY PROCESSES:</u>
uncoherent symmetric photons.
DECREASED CORRELATIONS BETWEEN TWIN BEAMS

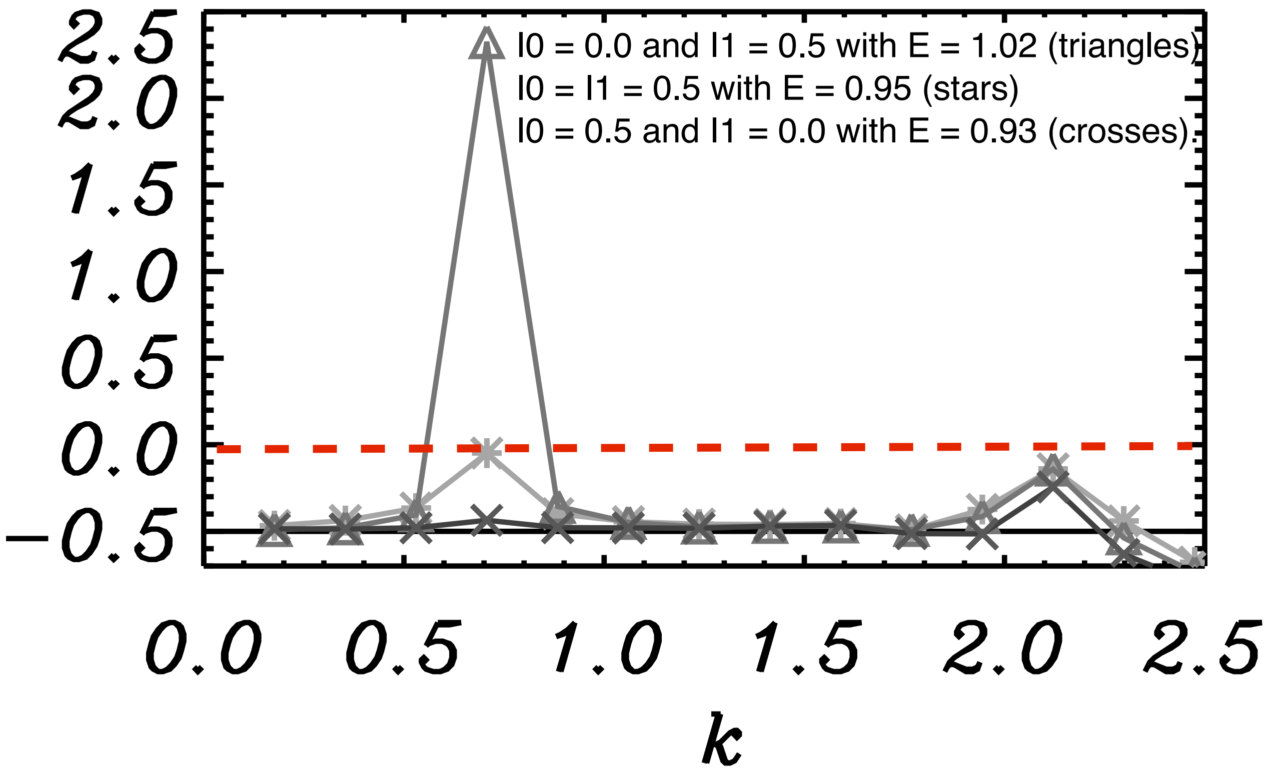
Zambrini, Barnett, Colet, San Miguel, EPJD **22**, 461 (2003)

TWIN BEAMS CORRELATIONS (with PC)

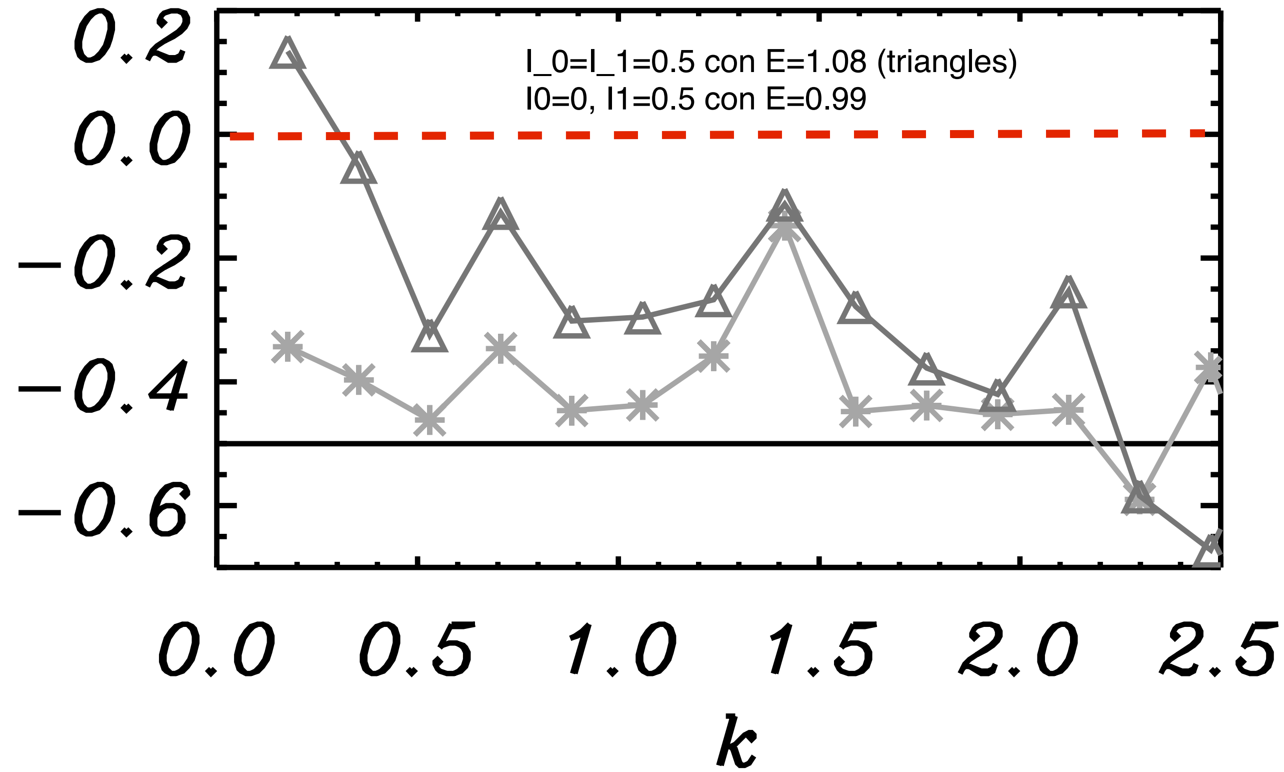
below threshold

$$\mathcal{V}(k) = \frac{\langle: [\delta \hat{N}_1(k) - \delta \hat{N}_1(-k)]^2 :\rangle}{\mathcal{N}_N(k)}$$

$n_p=2$



$n_p=1$



PC is at the origin of multimode processes even below threshold: incoherent processes degrade twin beams correlations

above threshold similar!

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MOMENTUM CONSERVATION

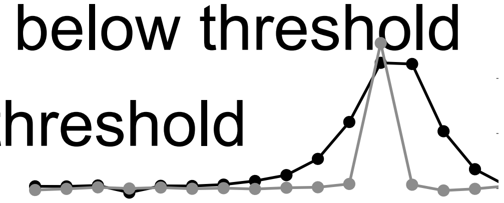
twin beams correlations

$$\mathcal{V}(k) = \frac{\langle : [\delta \hat{N}_1(k) - \delta \hat{N}_1(-k)]^2 : \rangle}{\mathcal{N}_N(k)}$$

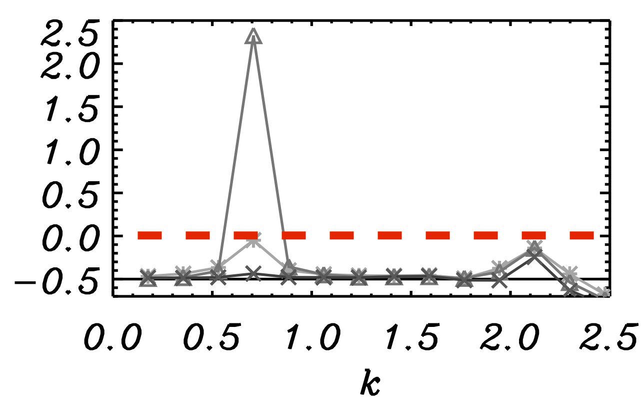
NO PC

perfect below threshold

above threshold



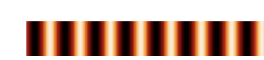
$k_c=2k_p$



conservation of transverse momentum

Grynberg & Lugiato (1993), Gomila &Colet (2002)

$$S_\perp = \int k(N_0(k) + N_1(k))dk$$

$\frac{:\Delta^2 S_\perp:}{\mathcal{N}_S}$	Δ_0	Δ_1
$\simeq -0.5$		
$\simeq 0$		
$\simeq -0.5, 0, 2....$		
$\simeq 0$		

quantum effect depends on (translational) symmetry and conservation (of momentum)

CONCLUSIONS

- PC in nonlinear cavities allow to tune the parametric (and MI) threshold
- twin beams correlations are changed due to secondary processes
- connection: quantum noise suppression vs. translational symmetry

IN PROGRESS

- explore role of wavelength and amplitudes of PC
- breaking of translational symmetry vs. 2 mode squeezing