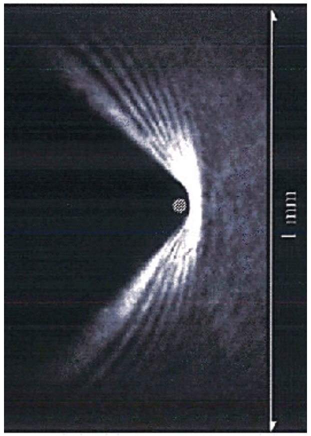
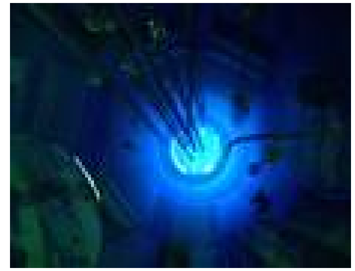


Expanding BEC against defect

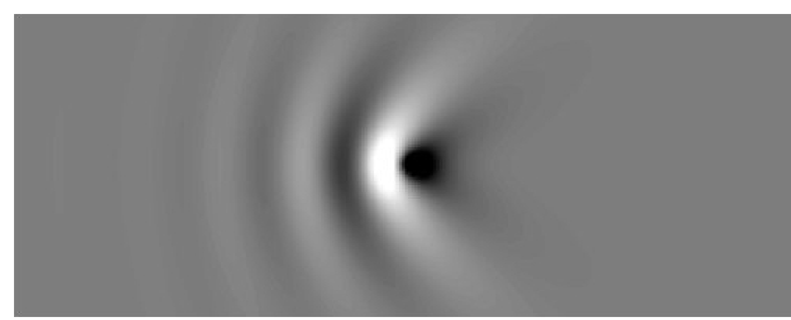


Cerenkov light

Jet breaking sound barrier

What do these effects have in common ?

Duck swimming on quiet lake



Real space Rayleigh scattering in solids

The Cerenkov effect revisited: from swimming ducks to Bose-Einstein condensates

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C. Ciuti (LPA-ENS, now Univ. Paris 7)

M. Wouters (Univ. Antwerp, Belgium. Now at EPFL)

S.X. Hu, L. A. Collins (LANL)

Experimental data on atomic BECs: E. Cornell, P. Engels (JILA)

What is the Cerenkov effect ??

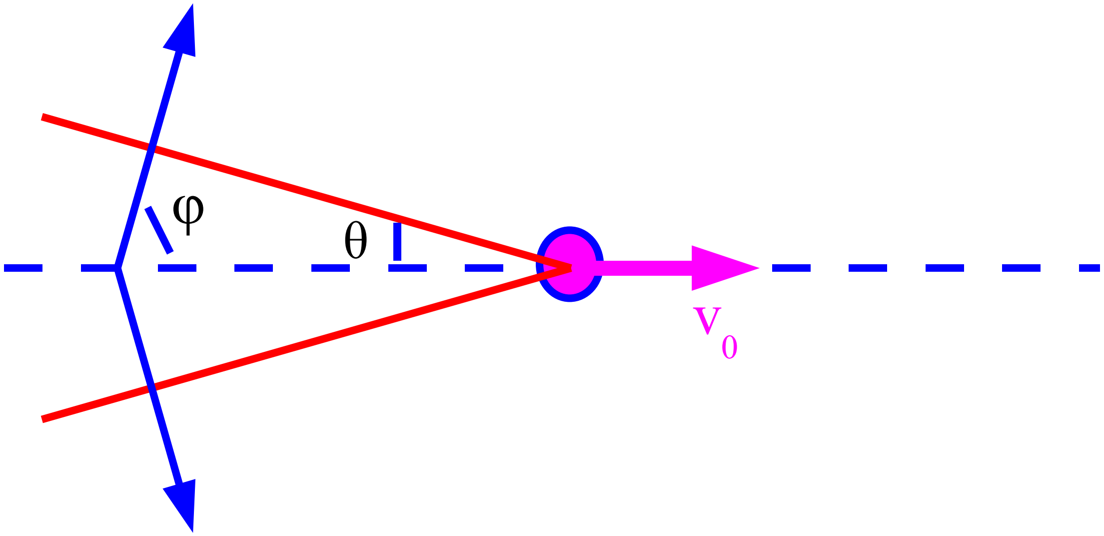
Charged particle uniformly moving at (relativistic) speed v_0

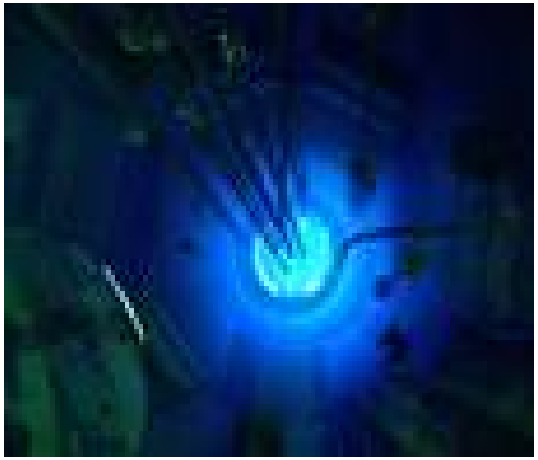
Non-dispersive medium of refraction index n, phase velocity $v_{ph} = c / n$

If $v_0 > v_{ph}$: light emitted by Cerenkov effect

Radiation emitted at angle: $\cos \varphi = v_{ph} / v_0$

Conical wavefront of aperture: $\sin \theta = v_{ph} / v_0$





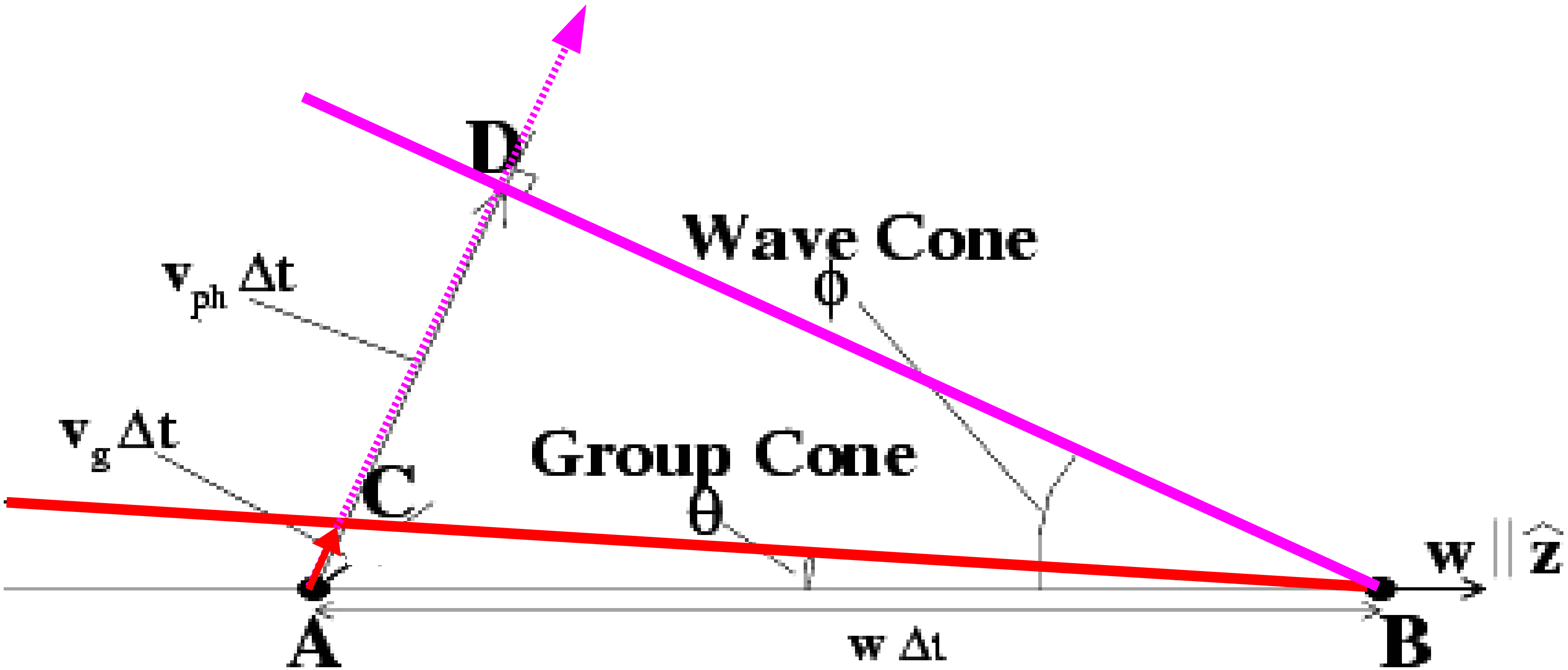
How I got interested in Cerenkov stuff (a long ago...)

Threshold speed: phase velocity $v_c = \min_k [\omega(k) / k]$

- What is role of group velocity v_{gr} in Cerenkov emission ?
- What happens in strongly dispersive, slow-light media

  in which $v_{gr} \ll v_c$?

Cerenkov emission in slow light media



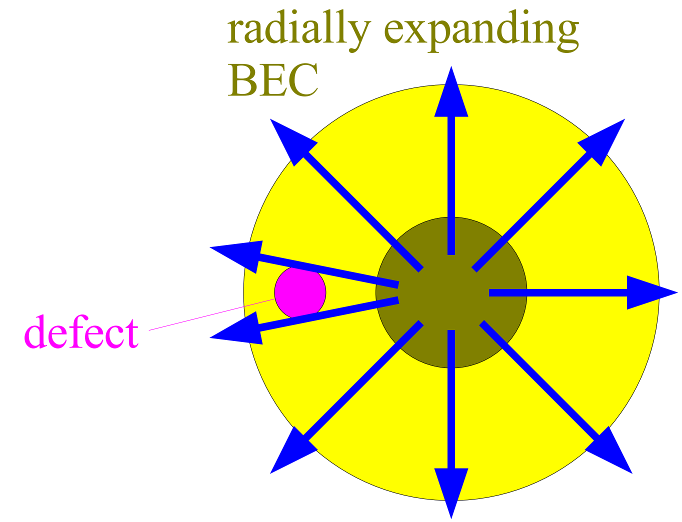
- (usual) **wave cone** $\cos\varphi = v_{ph} / v$ fixes far-field angle of emission
- **group cone** $\cos\theta = v_{gr} / v$ fixes spatial region where E field is peaked

I. M. Frank, Nucl. Instr. Meth. A **248**, 7 (1986)
I. Carusotto, M. Artoni, G. C. La Rocca, F. Bassani, PRL **87**, 064801 (2001)

Many years later...

Atomic Bose-Einstein condensate

- Harmonic trap suddenly inverted
- BEC expands
- Defect: blue-detuned laser beam
- Wave pattern created in density profile



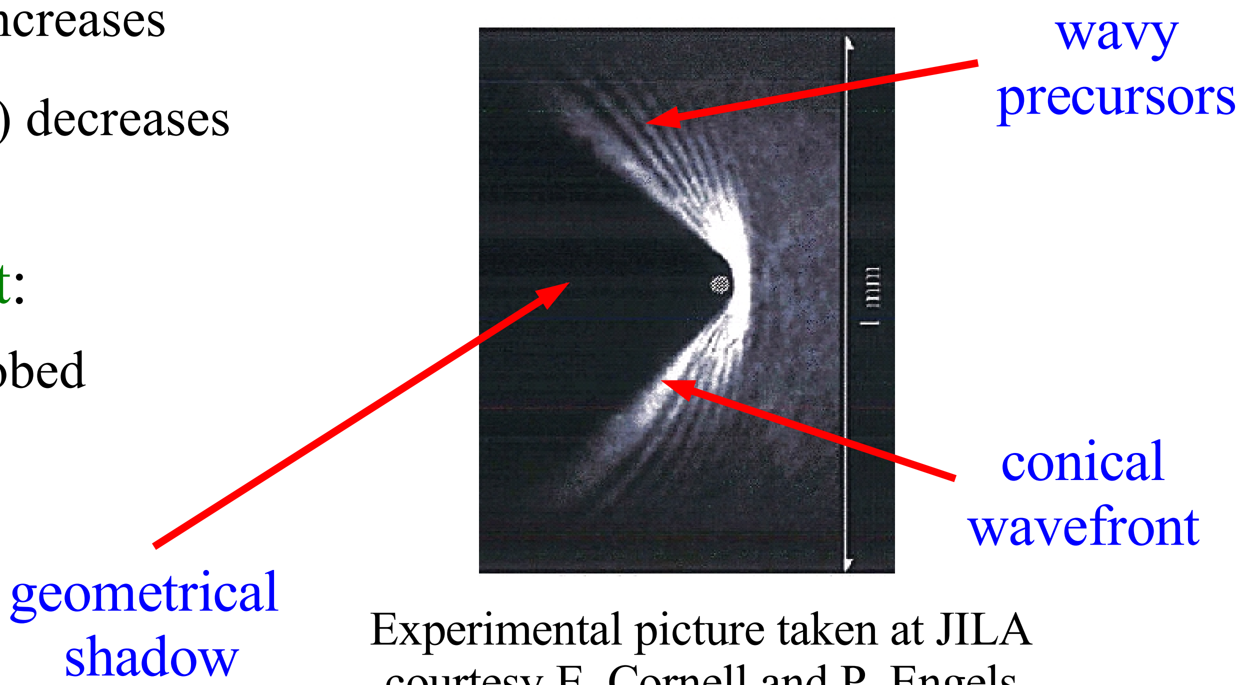
As time goes on:

→ local velocity v_0 at defect position increases

→ local density (and speed of sound c_s) decreases

After different expansion times t:

- different Mach numbers $M=v/c_s$ probed
- absorptive images



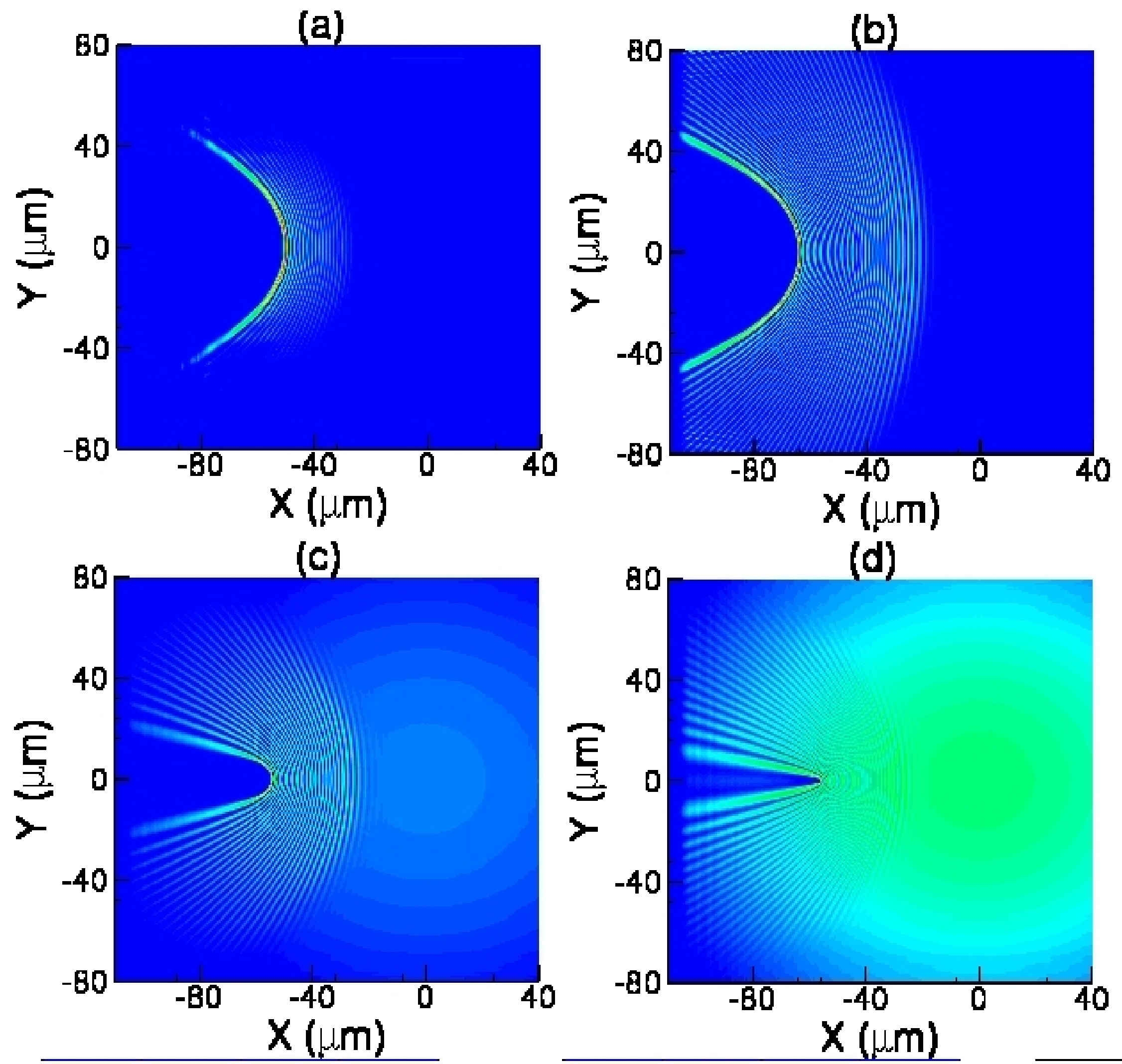
Experimental picture taken at JILA
courtesy E. Cornell and P. Engels

Brute force 3D GPE simulations

Different:
- expansion time t
- defect size w

Longer t → higher speed
a) t=33.6 ms, w=17 mm
b) t=50 ms, w=17 mm

Smaller defect → narrower shadow
c) t=38.4 ms, w=3.74 mm
d) t=38.4ms, w=0.374 mm



Good agreement with experiment, but not much physical insight !!

I.Carusotto, S.X.Xu, L.A. Collins, and A. Smerzi, Phys. Rev. Lett. **97**, 260403 (2006)

Theory of Bogoliubov-Cerenkov radiation

Uniform BEC flowing at constant speed v. BEC wavevector $\mathbf{k}_0 = m\,\mathbf{v}/\hbar$

Weak stationary defect potential: Bogoliubov linear response

$$i\hbar \frac{\partial}{\partial t}\delta\vec{\psi} = \mathcal{L}\cdot\delta\vec{\psi} + \vec{F}_d \longrightarrow \delta\vec{\psi}_d = -\left(\mathcal{L} - i\,0^+\,\mathbf{1}\right)^{-1}\cdot\vec{F}_d$$

Eigenvalues of L : dispersion of Bogoliubov excitations in moving BEC
as compared to fluid at rest: additional tilting term $\mathrm{v}\cdot(\mathrm{k}-\mathrm{k}_0)$

$$\omega(\mathbf{k}) = \mathbf{v}\cdot(\mathbf{k}-\mathbf{k}_0) \pm \sqrt{\frac{\hbar(\mathbf{k}-\mathbf{k}_0)^2}{2m}\left(\frac{\hbar(\mathbf{k}-\mathbf{k}_0)^2}{2m} + 2g\rho_0\right)}$$

➔ In defect rest frame, system time-invariant: excitation resonant for **k** modes such that $\omega(\mathbf{k}) = 0$

➔ In BEC rest frame standard Cerenkov condition $\omega_0(\mathbf{k}) - (\mathbf{k}-\mathbf{k}_0)\,\mathrm{v} = 0$ recovered !

IC and C.Ciuti, PRL 93, 166401 (2004)
I.Carusotto, S.X.Xu, L.A. Collins, and A. Smerzi, Phys. Rev. Lett. **97**, 260403 (2006)

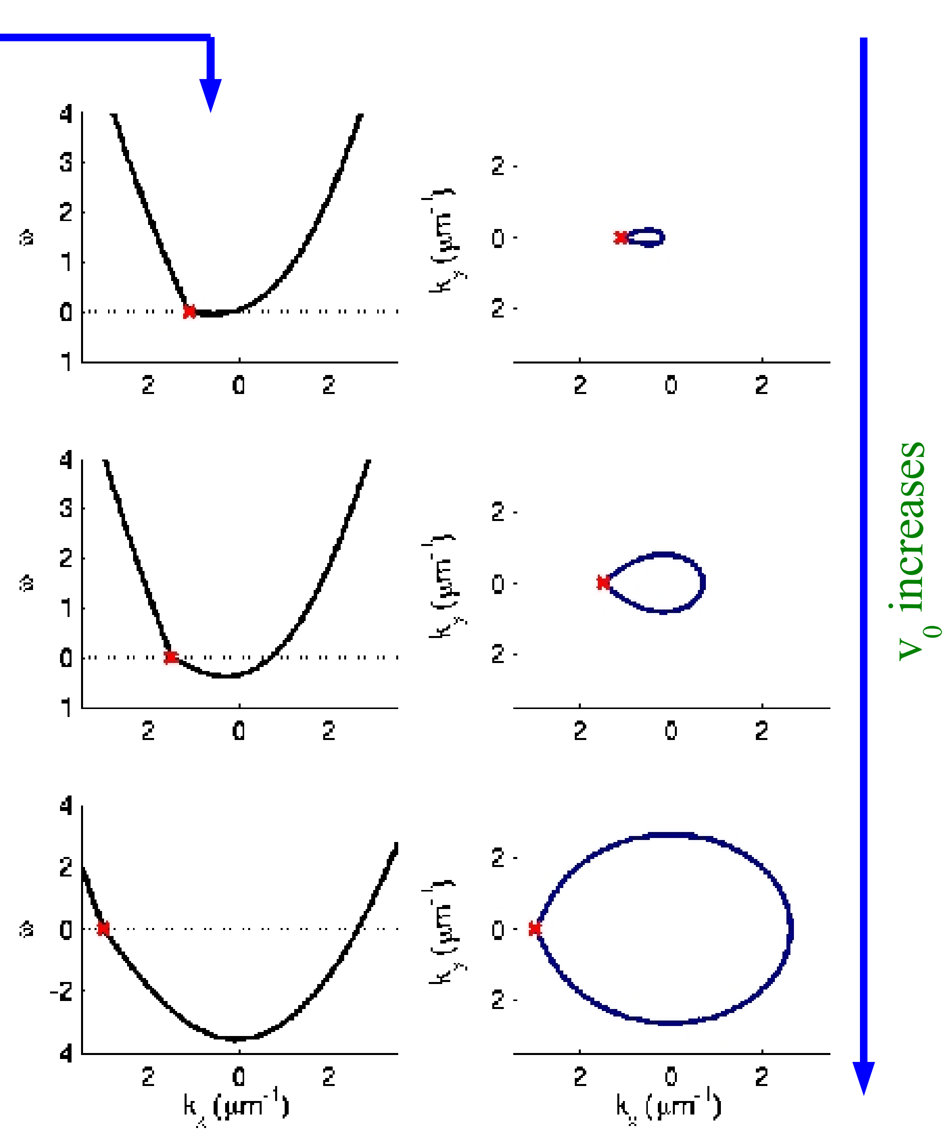
Theory of Bogoliubov-Cerenkov radiation (II)
k-space pattern

If $v_0 < c_s$ (c_s speed of sound):

- resonance condition never satisfied
- no radiative modes excited
- perturbation localized
  $\Rightarrow$ superfluid behaviour

If $v_0 > c_s$:

- a (deformed) ring of modes is resonantly excited
- ring gets wider for increasing v_0



I.Carusotto, S.X.Xu, L.A. Collins, A. Smerzi, PRL **97**, 260403 (2006)

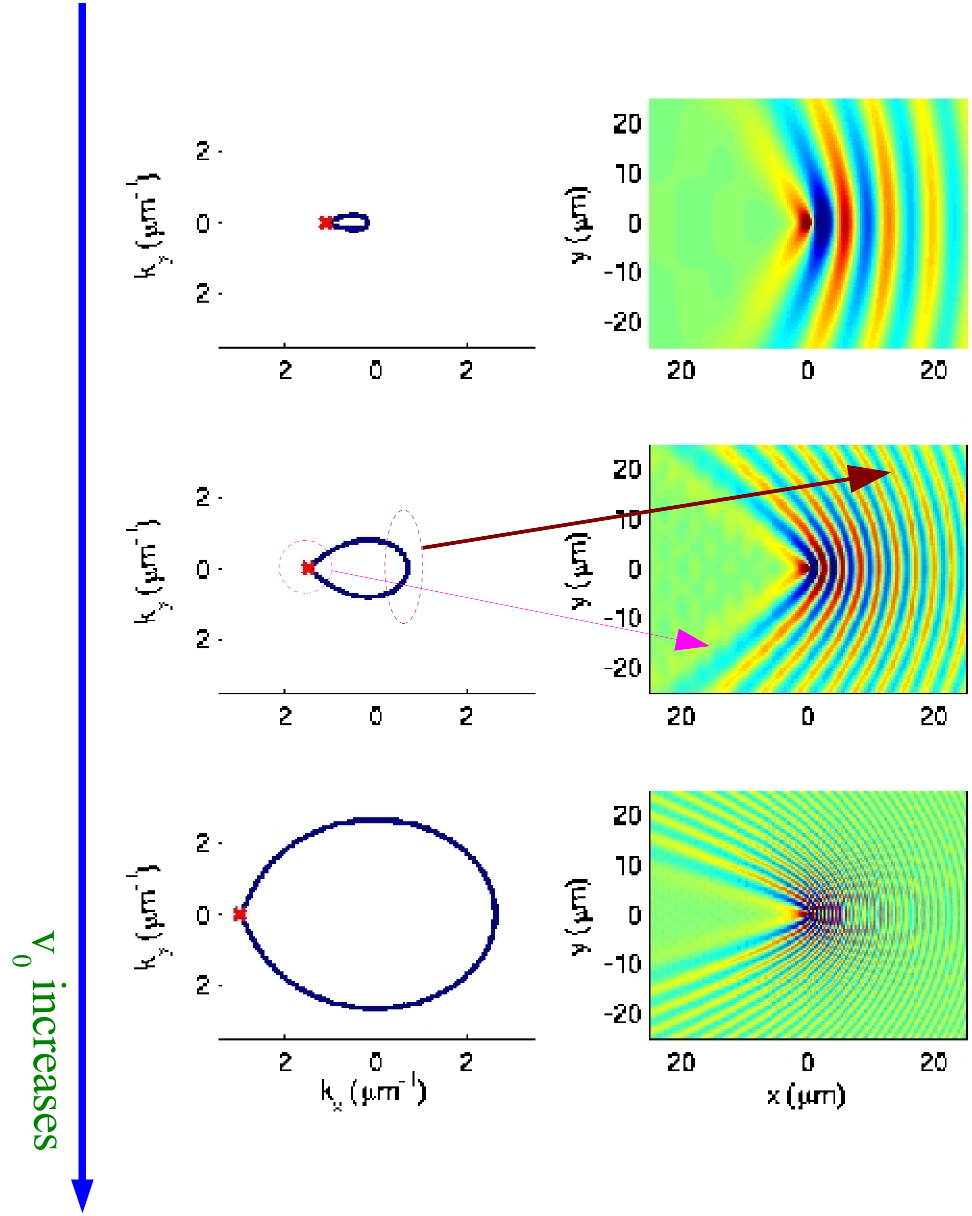
Theory of Bogoliubov-Cerenkov radiation (III)
real space pattern

Each resonantly excited mode:

- propagates from defect along straight line
- propagation velocity:
  group velocity: $v_g = \nabla_{\mathbf{k}} \omega(\mathbf{k})$
  orthogonal to locus of resonant **k** 's
- interferes with BEC:
  fringes at $\mathbf{q} = \mathbf{k} - \mathbf{k}_0$

Two regions in spatial pattern:

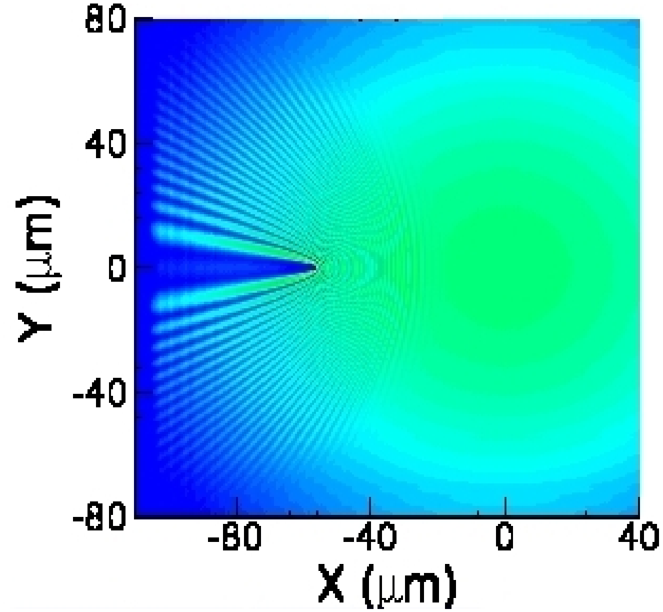
- Cerenkov cone:
  aperture $\cos\theta = v_{ph} / v_0$
- Parabolic precursors:
  single-particle scattering on defect



Comparison with GPE simulations

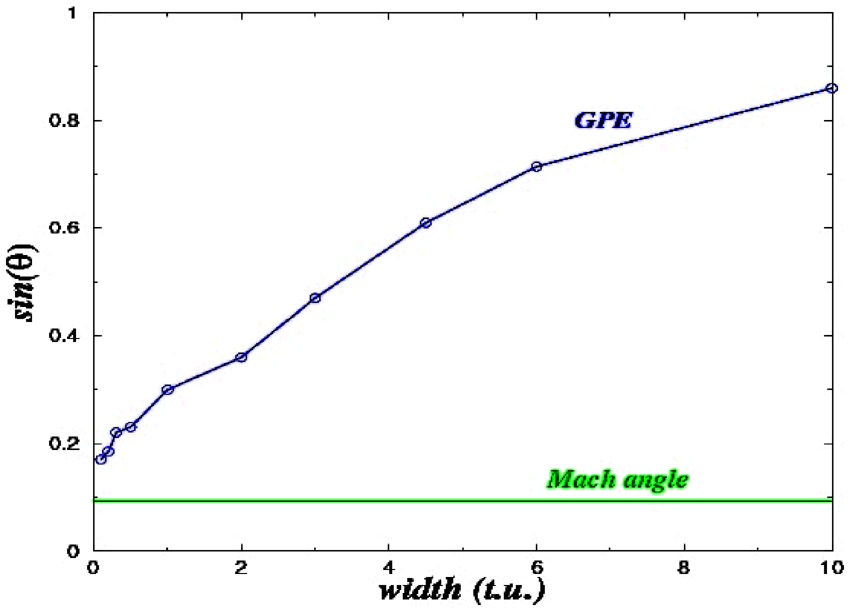
Pattern qualitatively similar, but in GPE:

- larger aperture of cone
- geometrical shadow behind the defect



Explanation: BEC expansion velocity is not uniform, but rather radial

- Cerenkov angle adds up to geometric shadow angle
- shadow angle decreases for decreasing defect size w
- in small defect limit: Cerenkov angle recovered



Convincing evidence this is Bogoliubov-Cerenkov emission in a quantum fluid !!

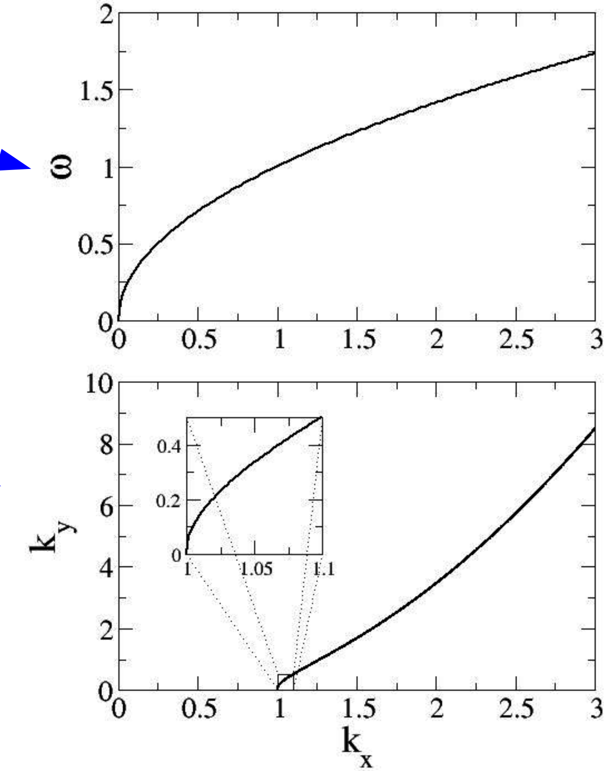
Swimming ducks on a quiet lake

Spatial pattern qualitative similar to Cerenkov effect...
... is there a connection ??

Cerenkov theory applied to swimming ducks

Surface waves: modelled by sqrt dispersion law

Locus of resonantly excited modes

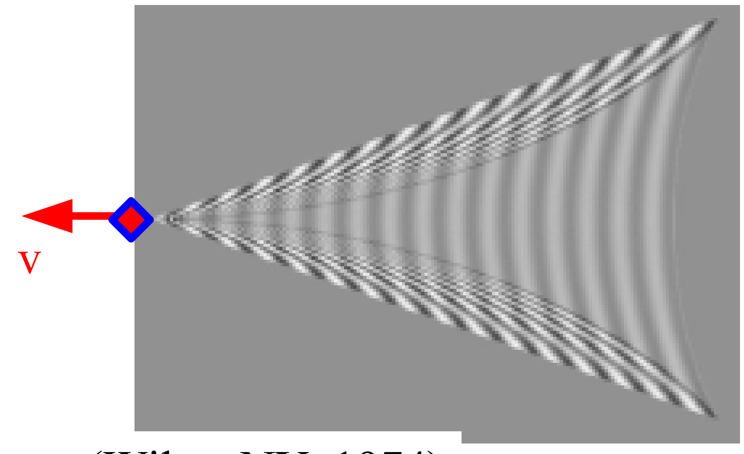


Many interesting new features:

- limited range of group velocity angles $\tan\theta_g < 1/\mathrm{sqrt}(8)$,
  max value of θ_g does not depend on v

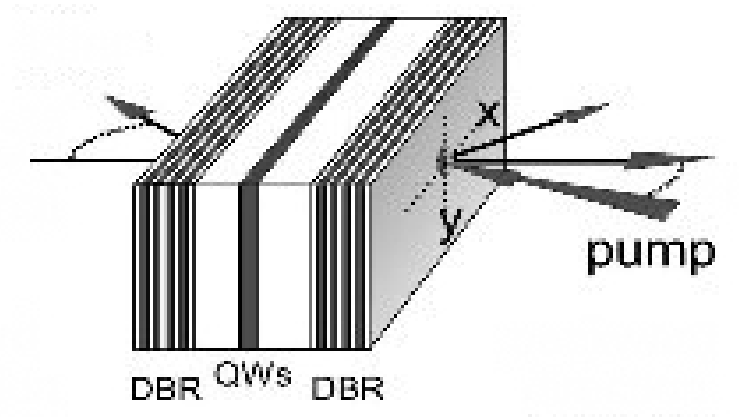
- for each position in space: two k vectors available
  ⇒ two intersecting patterns

- duck form factor (of size σ) limits range of excited k vectors.
  Emission suppressed if $v^2 << g\,\sigma$.
  For σ=20 cm v_{cr}=1.4 m/s (realistic!!)



see e.g.: G. B. Whitham, *Linear and nonlinear waves* (Wiley, NY, 1974)

Moving light fluids in planar optical cavities



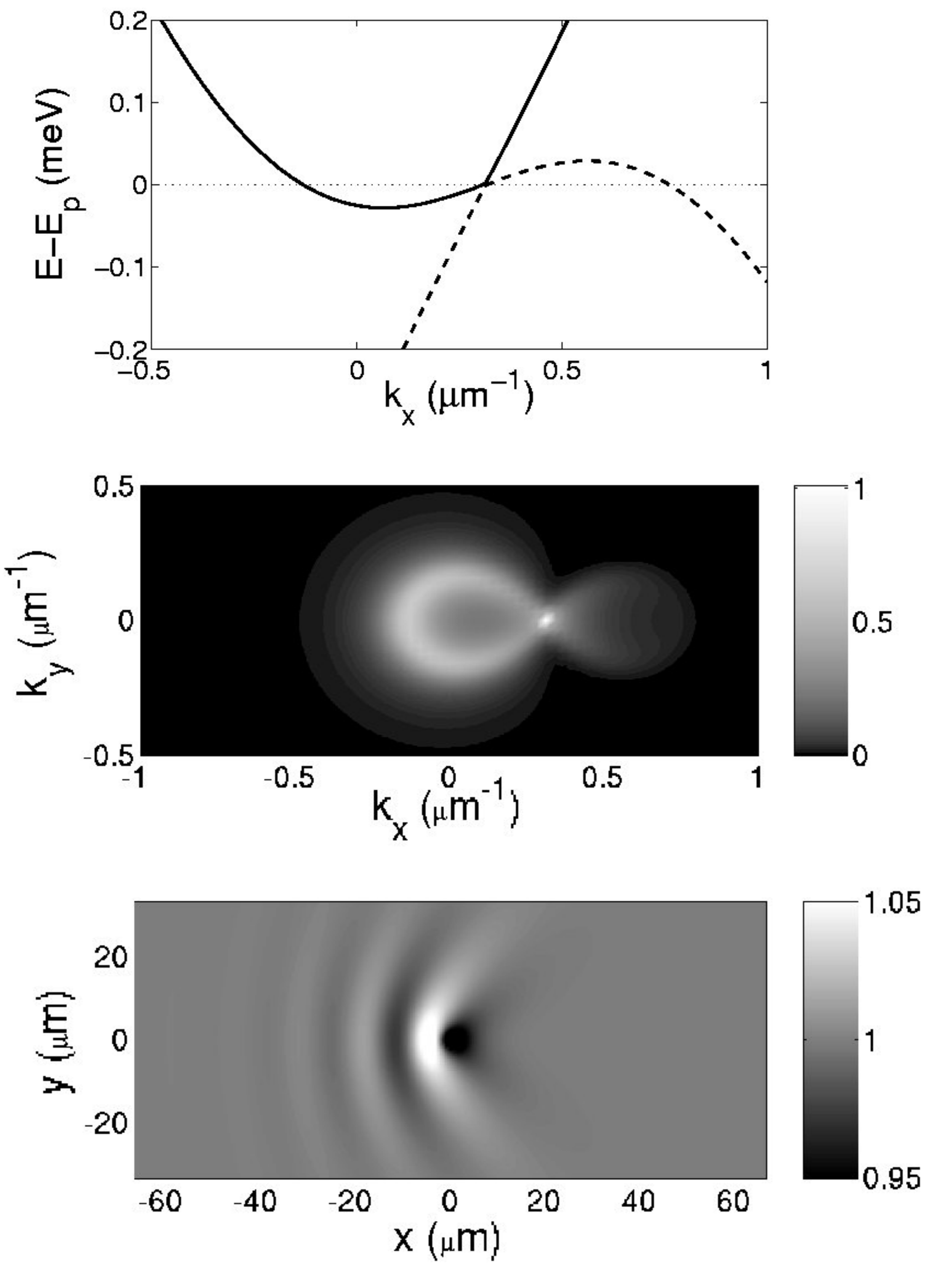
- Photon fluid created by coherent incident laser beam
- Flow speed controlled by incident wavevector k_p
- Photon-photon interactions : $\chi^{(3)}$ optical nonlinearity, polariton-polariton collisions
- Cavity roughness provides defects

Cerenkov excitation of Bogoliubov modes in moving light fluid

Experimental signal: transmitted and/or reflected light

- far field gives k-space intensity pattern
- near field gives real-space intensity pattern

Flow against a defect: Cerenkov emission



Incident laser on resonance with cavity

⇒ standard Bogoliubov dispersion

Cavity damping:

- smearing of k-space pattern
- spatial decay of x-space pattern far from defect

IC and C.Ciuti, PRL 93, 166401 (2004)

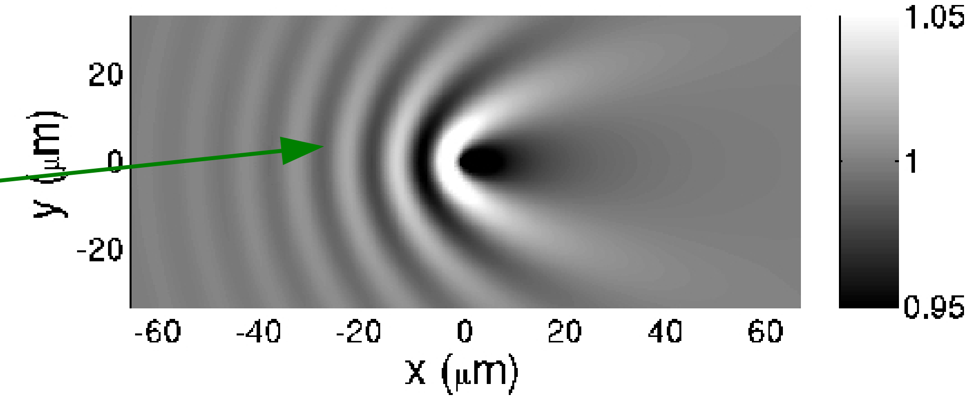
Increasing light intensity: superfluid behaviour

direction of flow

c_s increases with intensity

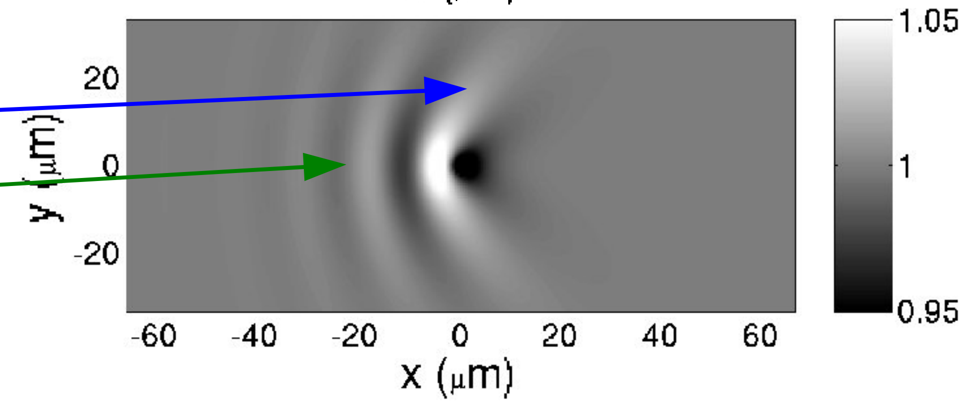
Linear regime $c_s = 0$

- parabolic wavefronts



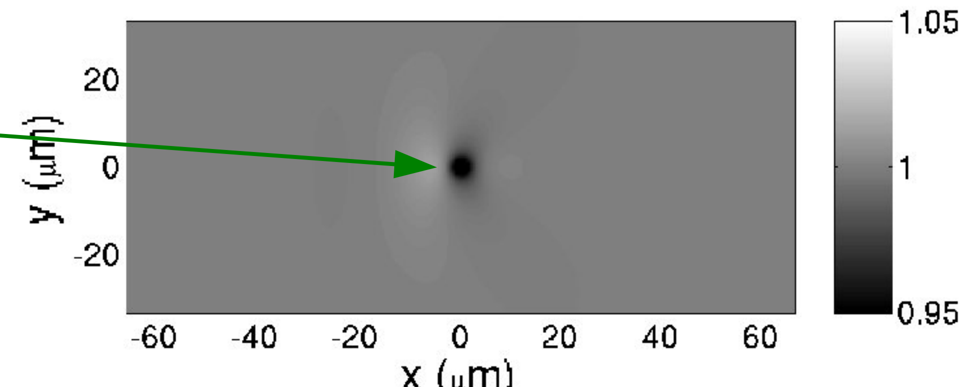
Super-sonic regime $c_s > v_0$:

- Cerenkov cone
- parabolic precursors

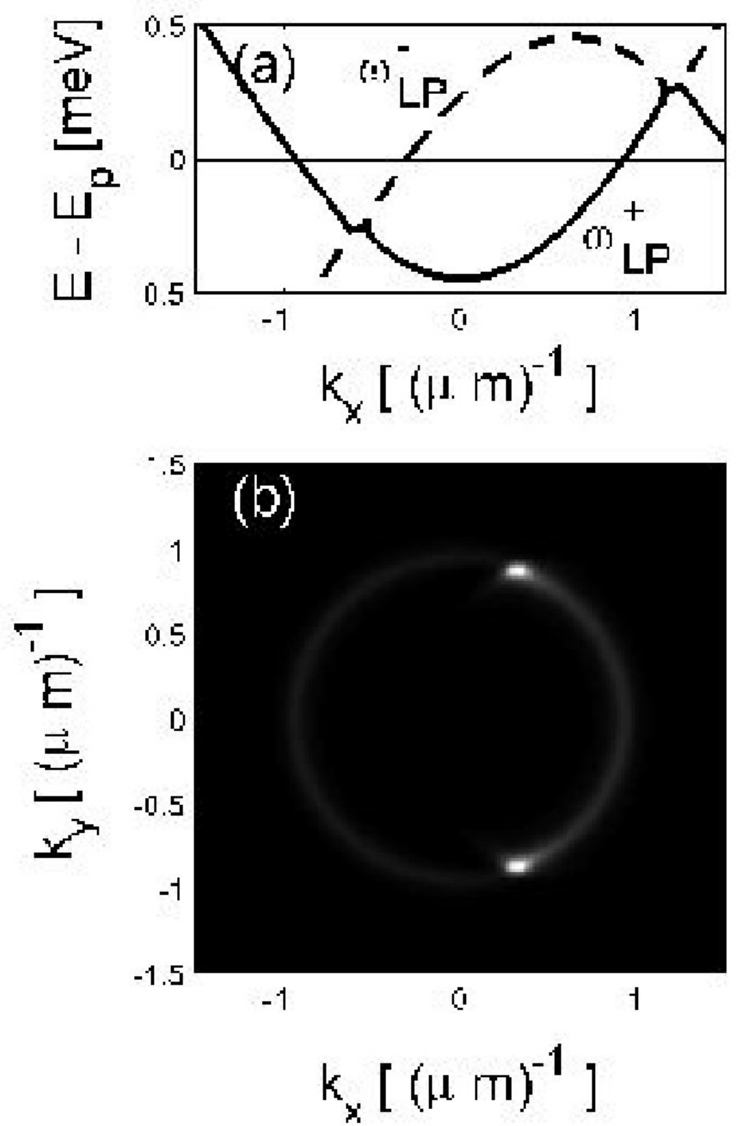


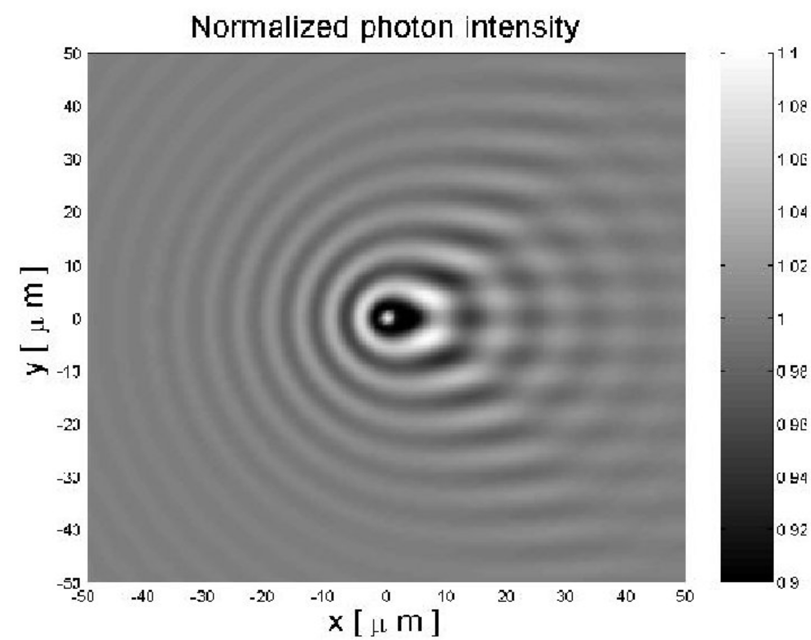
Sub-sonic regime $c_s > v_0$

- localized perturbation
- polariton superfluid



Novel features: zebra-Cerenkov effect





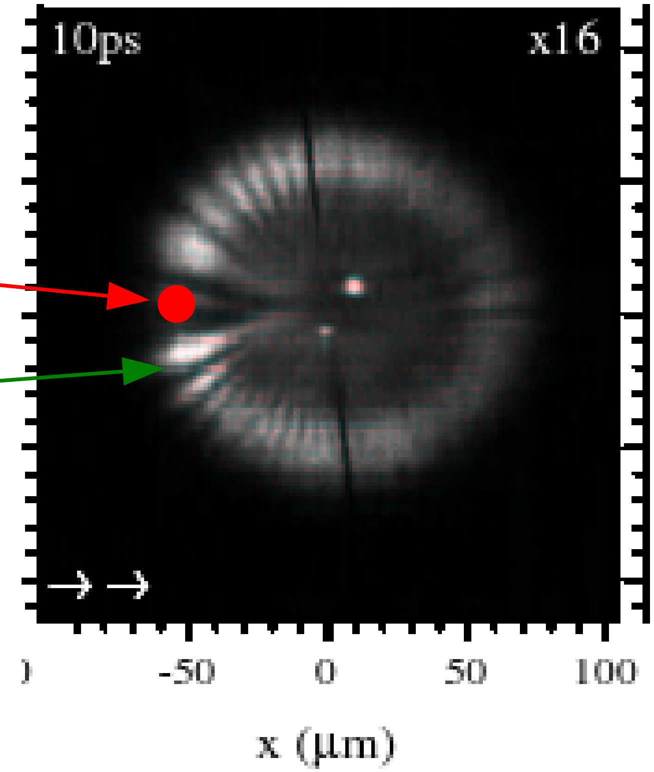
- Concentric rings: usual RRS ring
- Zebra pattern: narrow k-space peaks, precursor of parametric oscillation
- Many other shapes possible by tuning angle, frequency, intensity ...

C.Ciuti and IC, Phys. Stat. Sol. (b) 242, 2224 (2005). Experiment recently started at LKB-P6

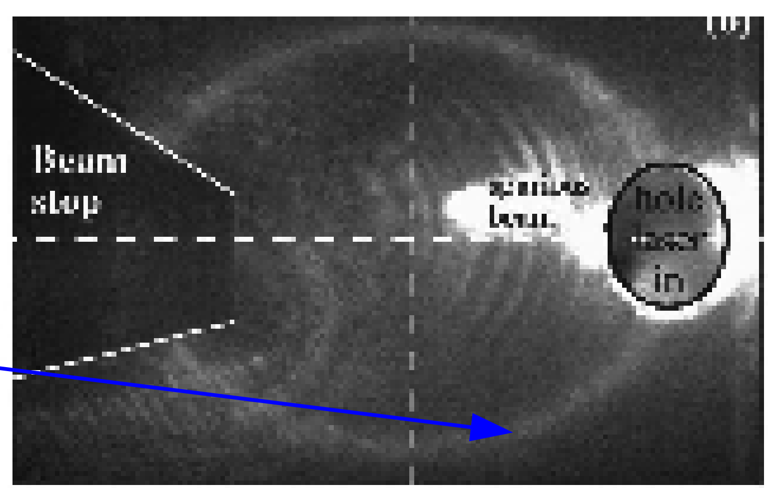
Preliminary experimental data: linear regime

Polariton cloud expanding against a defect

Real space pattern: fringes



k-space pattern
Resonant Rayleigh
scattering ring



Experimental data:
Langbein, 2002 (above)
Houdré, 2000 (below)

Bogoliubov modes of a non-resonantly pumped polariton Bose-Einstein condensate

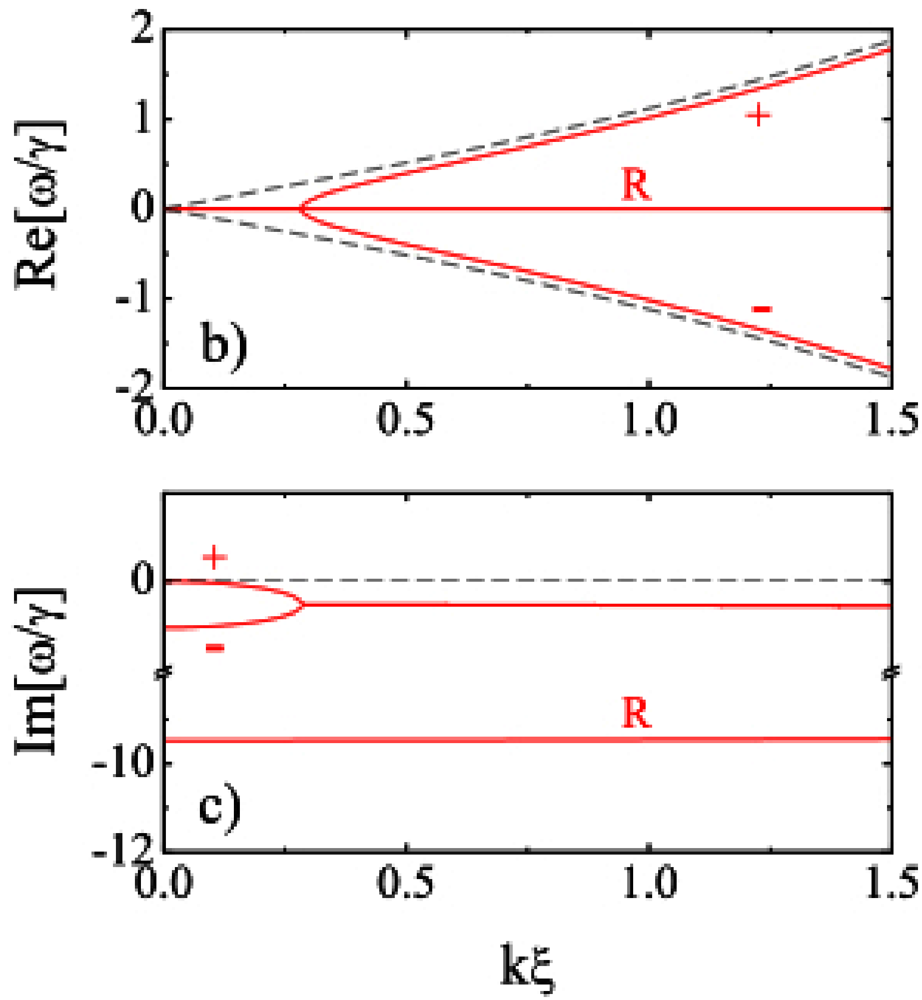
Linearize non-equilibrium GPE

- Reservoir R mode at $-i\,\gamma_R$
- Condensate modes ± at:

$$\omega_{\pm}(k) = -\frac{i\Gamma}{2} \pm \sqrt{[\omega_{Bog}(k)]^2 - \frac{\Gamma^2}{4}}$$

with:

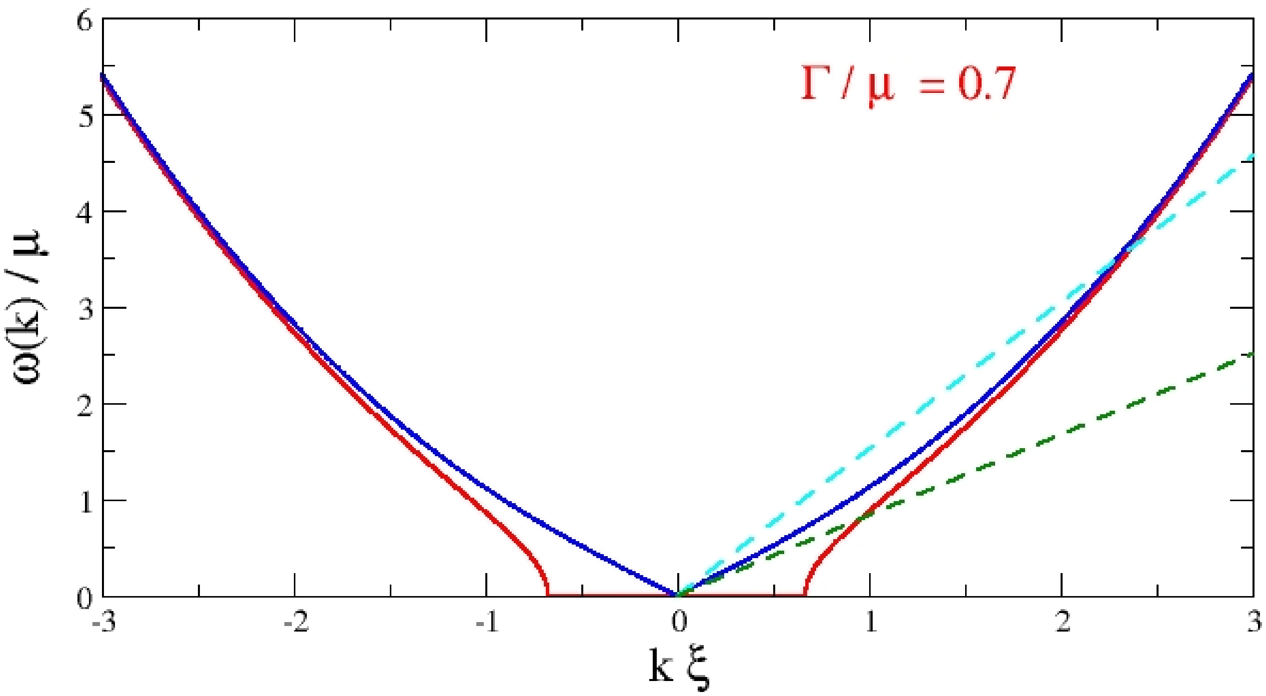
$$\omega_{Bog}(k) = \sqrt{\frac{\hbar k^2}{2m_{LP}}\left(\frac{\hbar k^2}{2m_{LP}} + 2\,\mu\right)}$$



→ Goldstone sound mode is diffusive !!!

M. Wouters and IC, *Excitations in a non-equilibrium polariton BEC*, Phys. Rev. Lett. **99**, 140402 (2007)

Consequences on superfluidity of polariton BECs



Naïf Cerenkov-Landau argument:

- Landau critical velocity $v_L = \min_k[\omega(k) / k] = 0$ of non-equilibrium BEC
- Any moving defect expected to emit phonons

But nature is always richer than expected...

Low v :

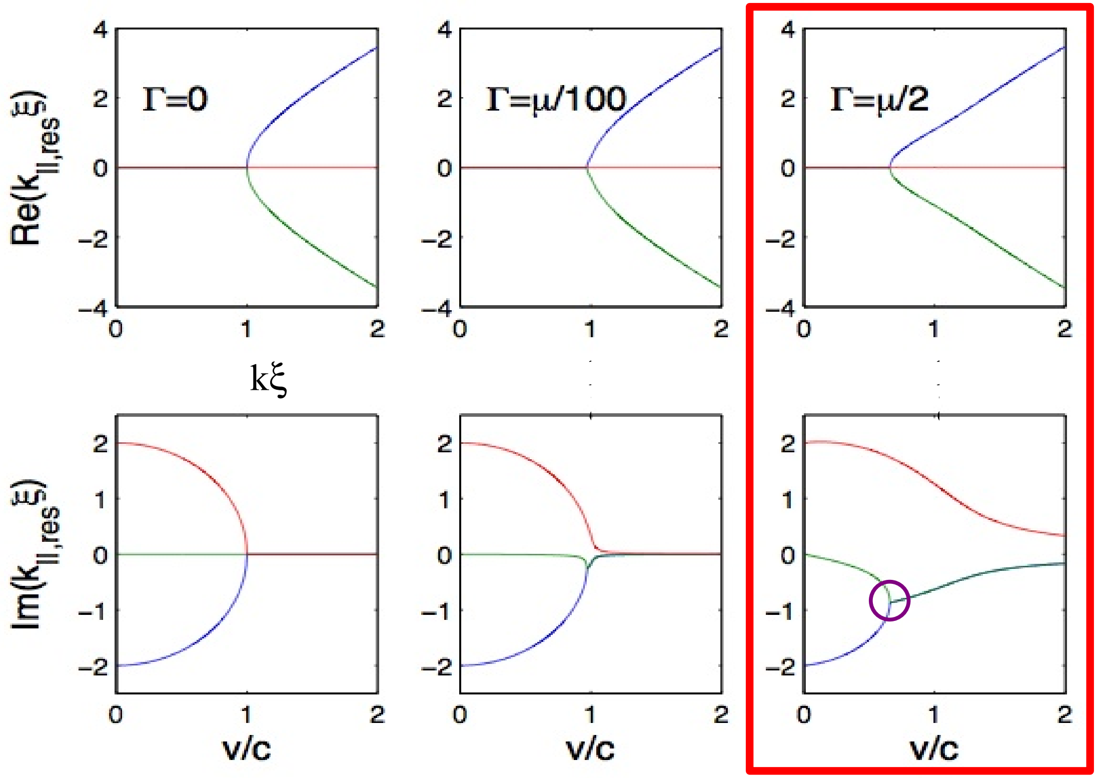
- emitted $k_{\parallel}$ purely imaginary
- no real propagating phonons
- localized perturbation around defect

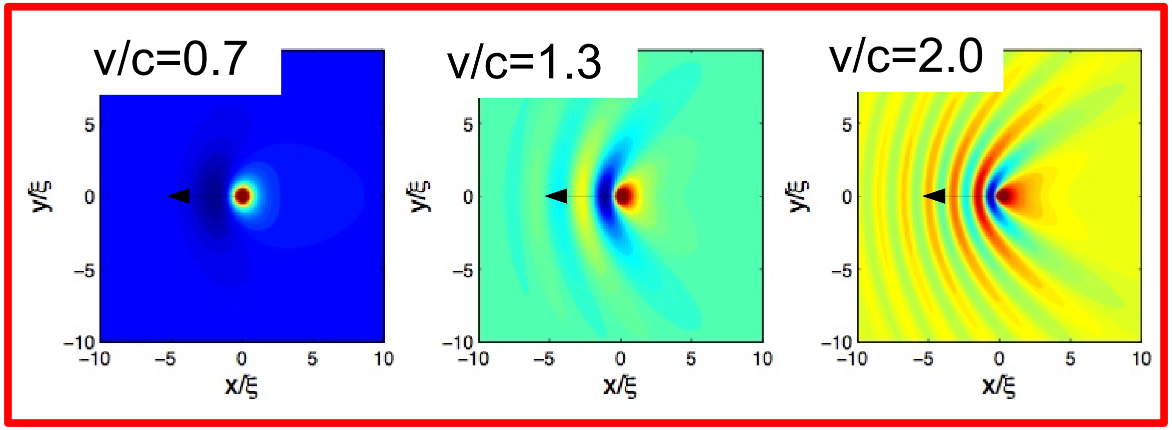
Critical velocity $v_c < c$:

- corresponds to bifurcation point
- decreases with Γ / μ

High v:

- emitted propagating phonons:
  - → Cerenkov cone
  - → parabolic precursors
- spatial damping of Cerenkov cone





Conclusions

General description of Cerenkov wave emission by uniformly moving sources and/or in uniformy moving media

A variety of systems to which it can be applied

- slow light media: wave vs. group cones

  IC, G.C. La Rocca, M. Artoni, F. Bassani, PRL **87**, 064801 (2001)

- expanding atomic BEC against defect potential of blue-detuned laser:

  Bogoliubov-Cerenkov emission of phonons, theory and experiment in agreement

  IC, S.X.Xu, L.A. Collins, and A. Smerzi, PRL **97**, 260403 (2006)

- swimming ducks on a quiet lake surface: complex pattern of surface waves

  well-known from hydrodynamics, but still interesting...

- moving light fluids in nonlinear planar cavities:

  peculiar dispersion law produces novel Cerenkov patterns

  IC and C.Ciuti, PRL **93**, 166401 (2004), C. Ciuti and IC, Phys. Stat. Sol. (b) **242,** 2224 (2005)

- polariton condensates: superfluidity beyond the naif Landau-Cerenkov criterion

  M. Wouters and IC, PRL **99**, 140402 (2007) ; preprint arXiv:0707.1446


THANKS FOR YOUR
ATTENTION !!!