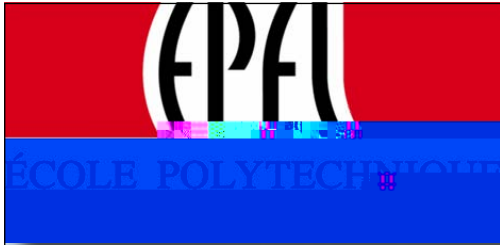


Test





*Quantum Optoelectronics Laboratory
Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland.*

Vortices and Superfluidity in Exciton-Polariton Condensates

My agenda is : How to turn a solid into a superfluid ?

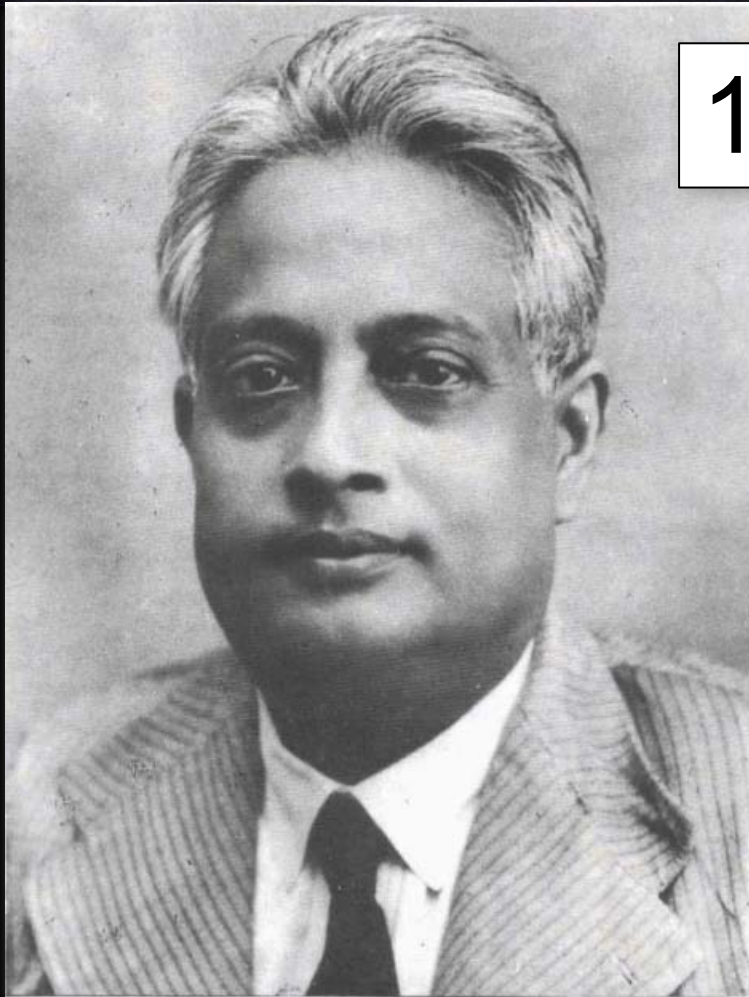


- Bose Einstein condensation
- A few words on polaritons
- Polaritons and vortices
- Polaritons and superfluidity
- What's next?



Superfluid Helium

1924



Satyendra Nath Bose



Albert Einstein

The Fifth state of matter



ex. He Atoms



Less than 1 μK for Rubidium



70

&

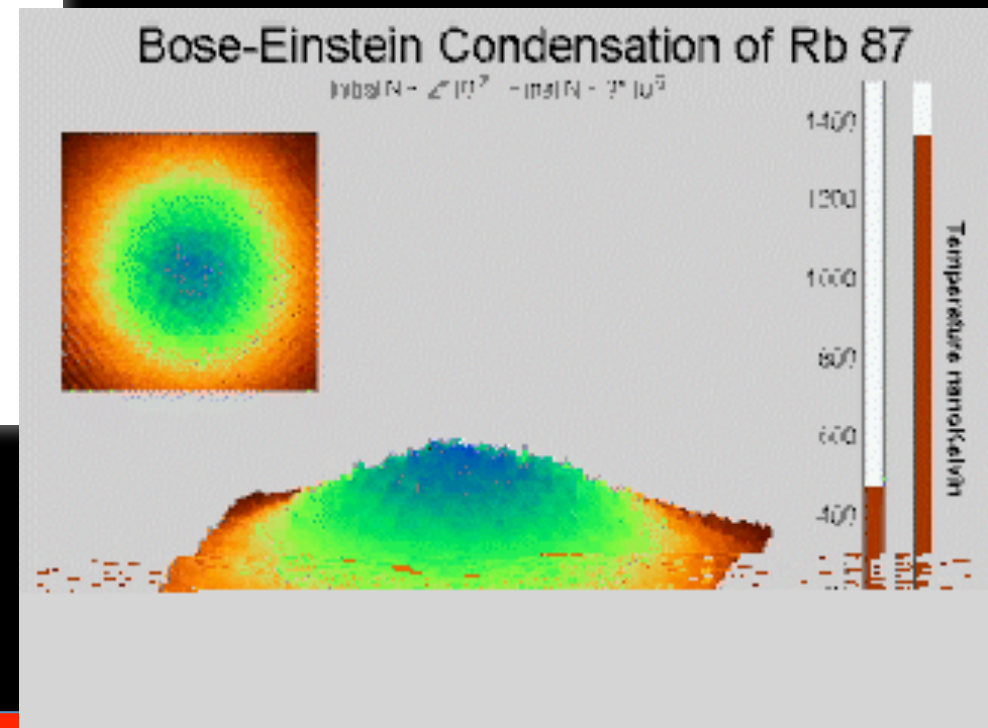
It does not matter
how slowly you go so
long as you do not
stop.



Confucius

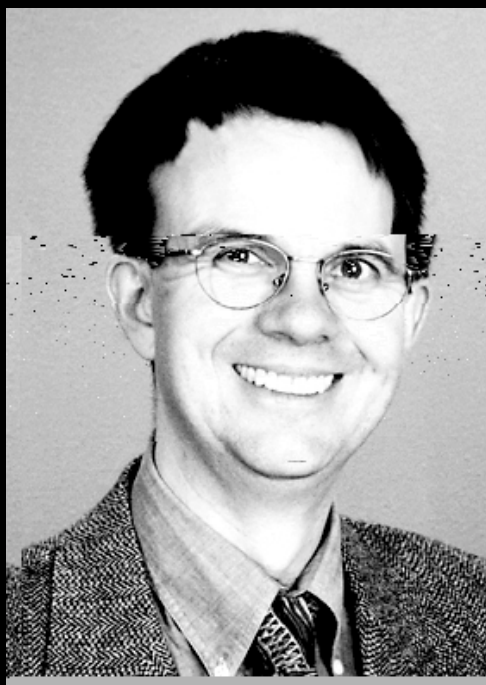
孔子

Bose-Einstein condensation of Rubidium atoms



Cornell et al. Science **269**, 198 (1995)

2001



Eric Cornell



Wolfgang Ketterle



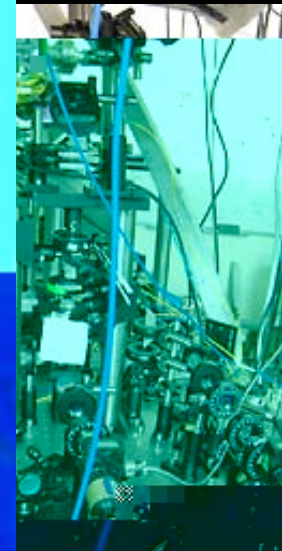
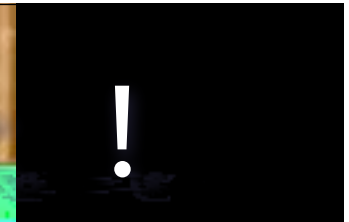
Carl Wieman

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".



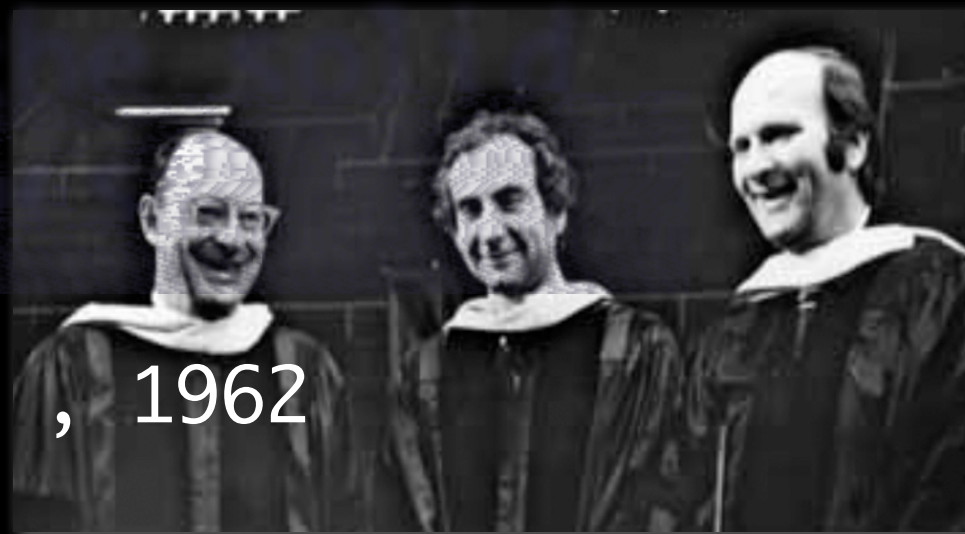
Nobelprize.org

The Official Web Site of the Nobel Prize



Why not in the

live



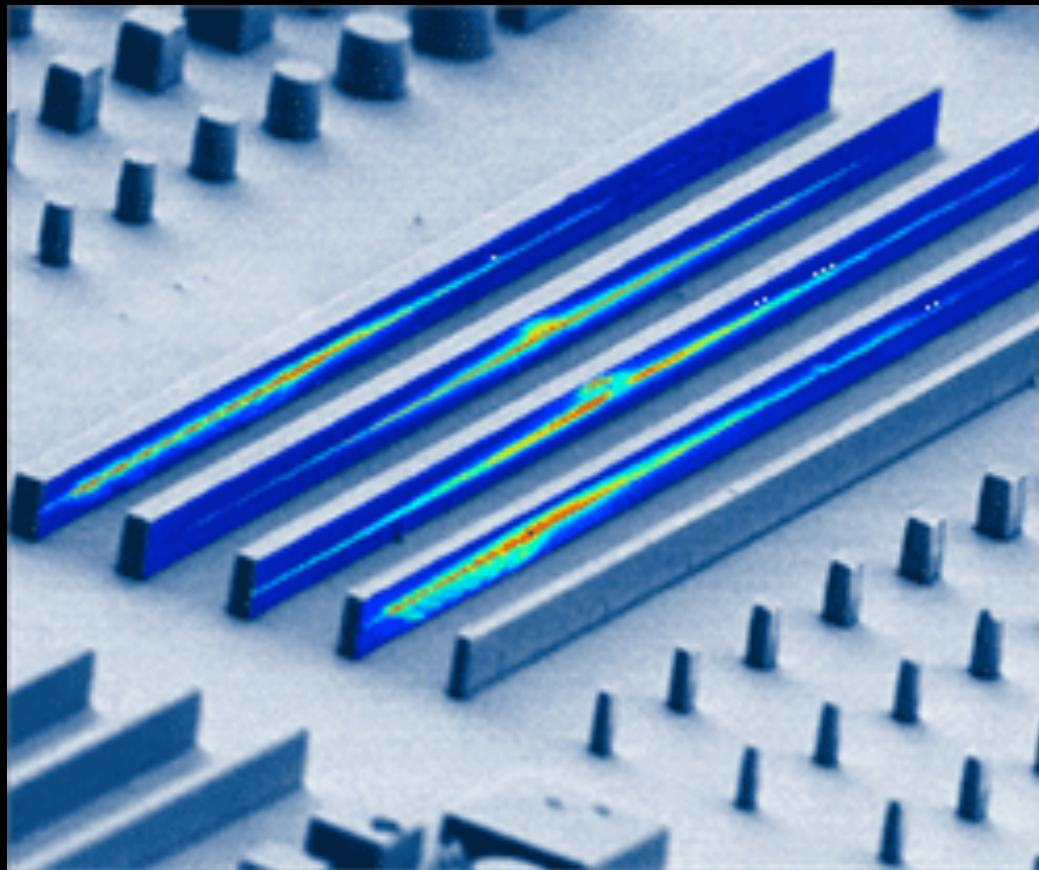
, 1962

,

10 000

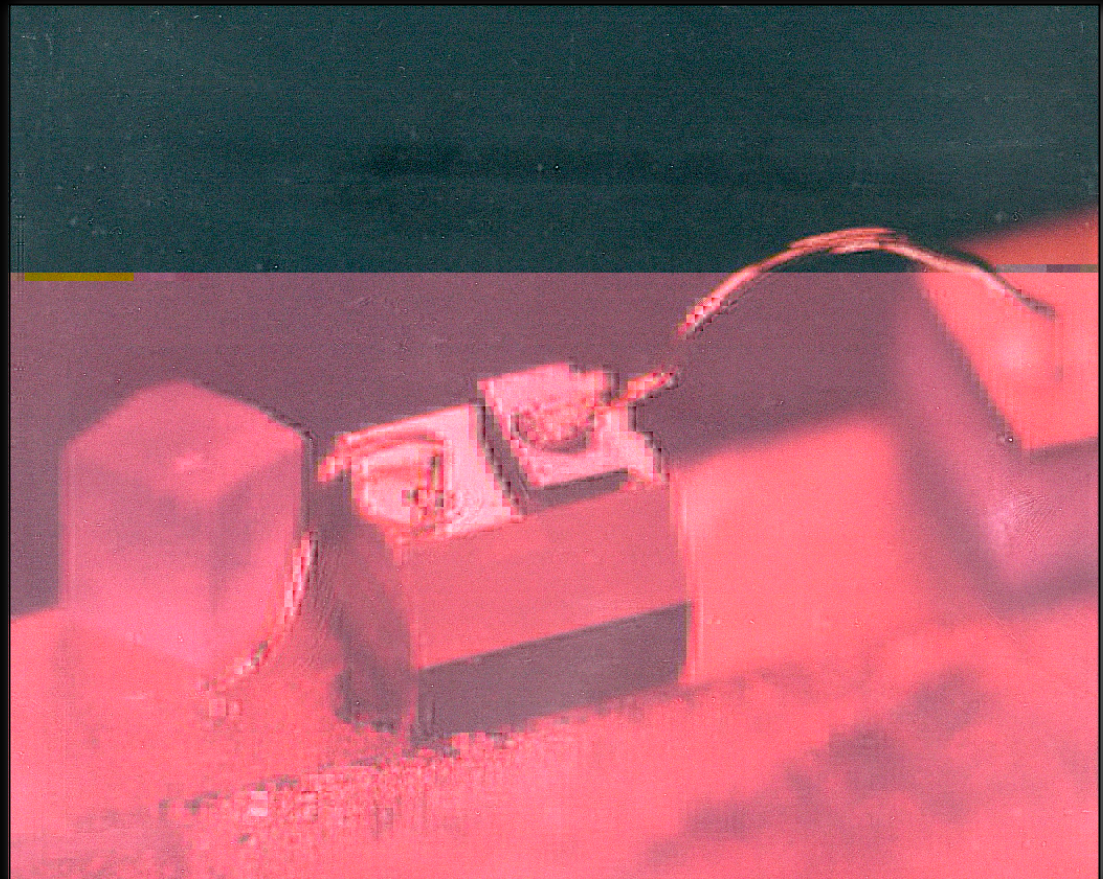
,

We use polaritons



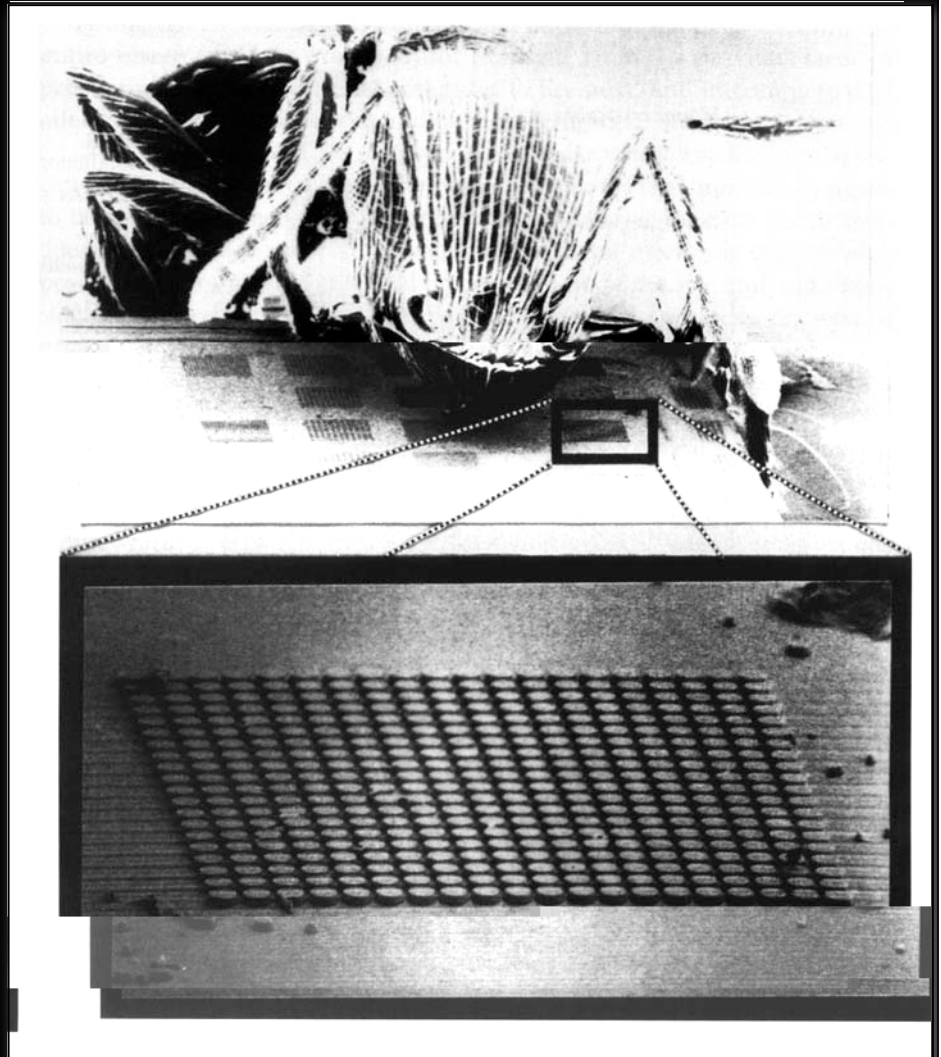
CNRS Press, , Courtesy Jacqueline Bloch

Origin of the idea?

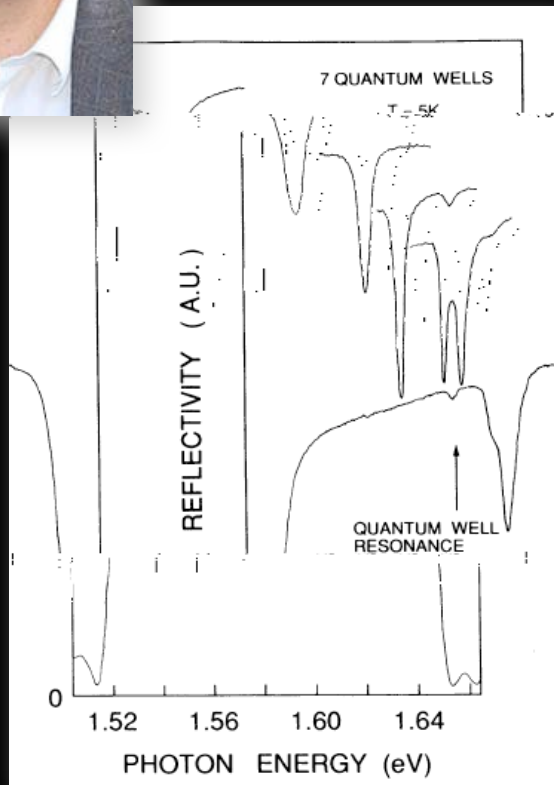


Vertical cavity surface emitting laser : VCSEL

%



Claude Weisbuch

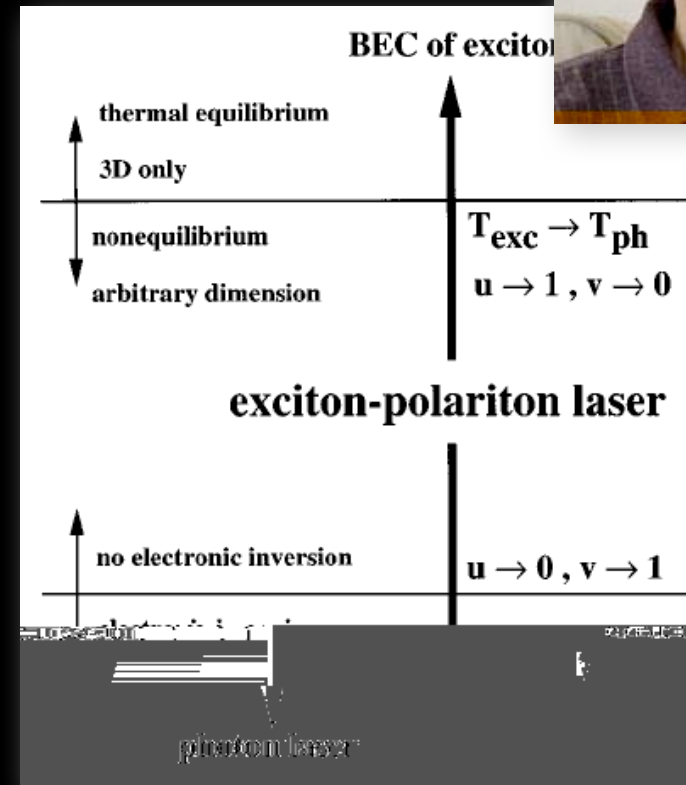


PRL, 69, 3314 (1992)



UC SANTA BARBARA
engineering and the sciences

Atac Imamoglu

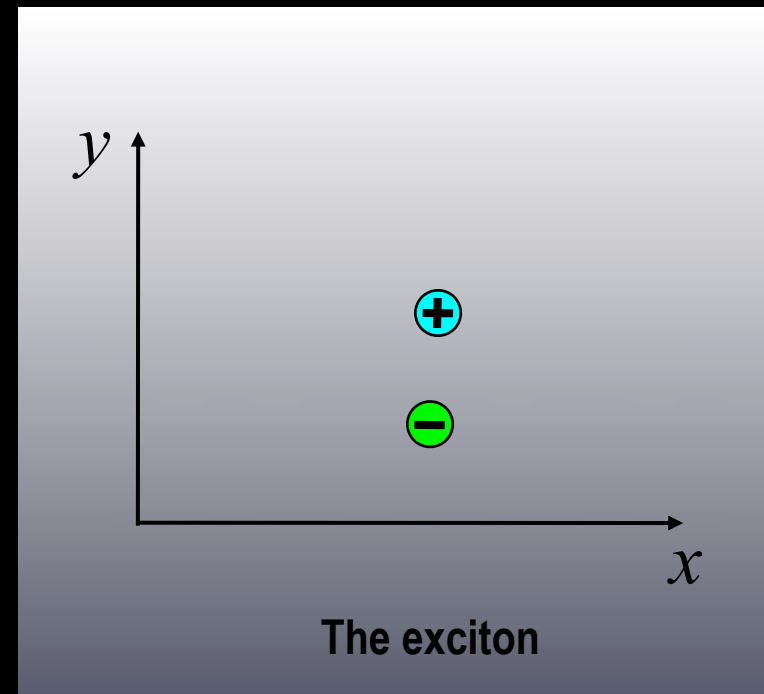
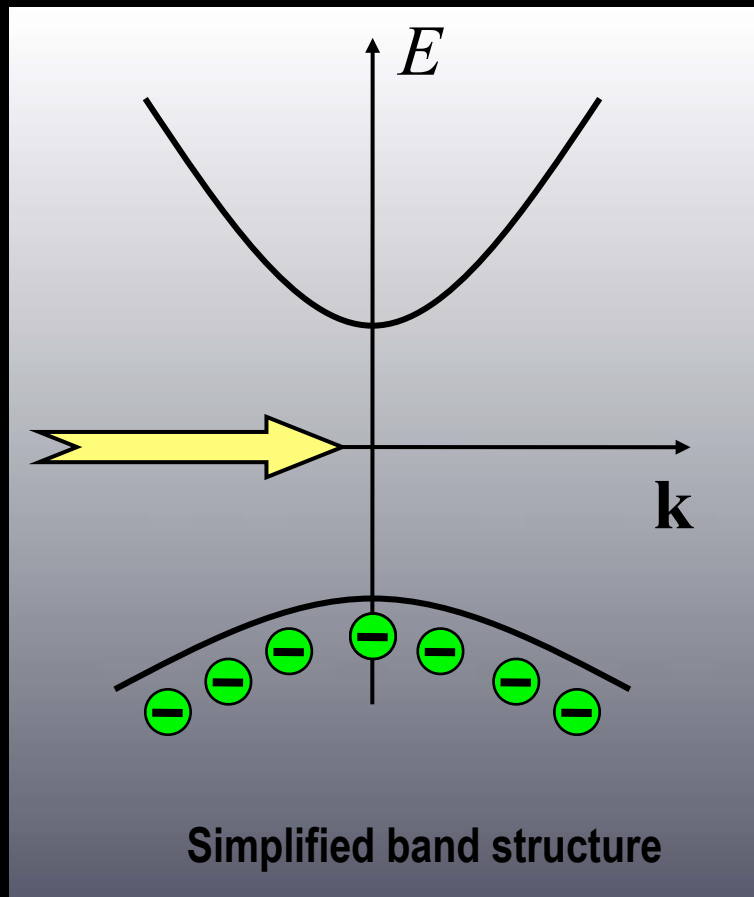


PRA, 53, 4250 (1996)

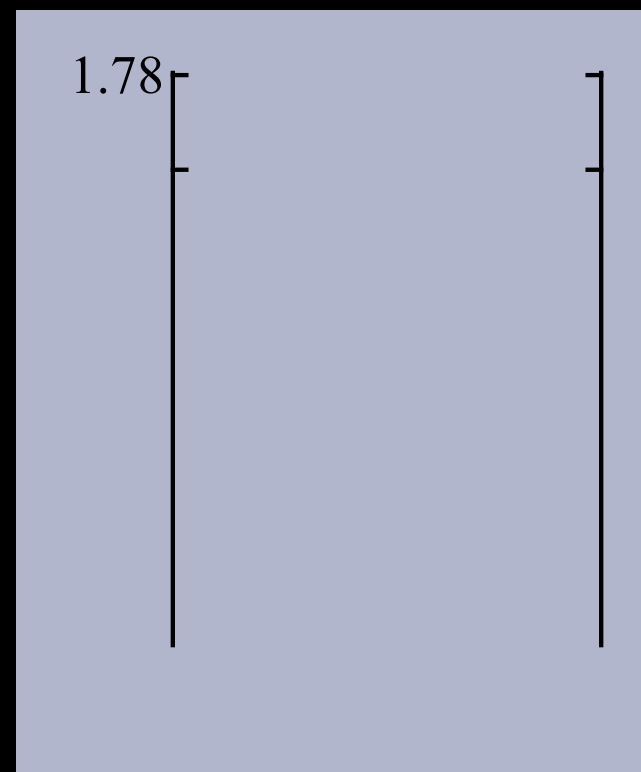
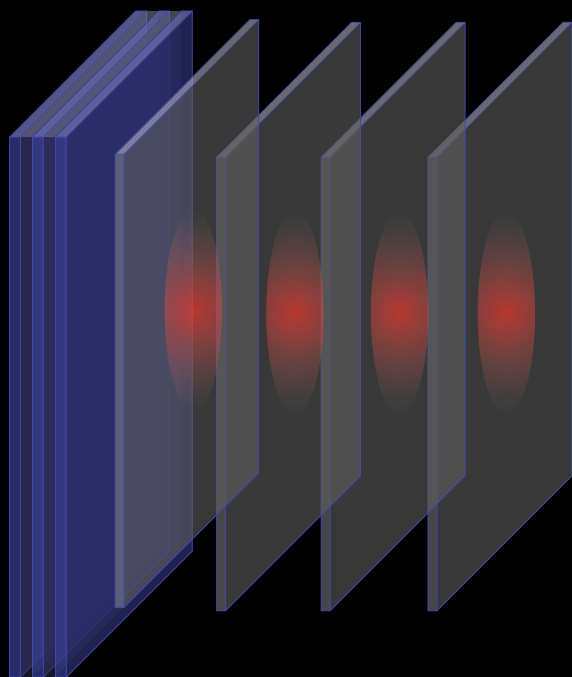


Eidgenössische
Technische Hochschule
Zürich

Exciton in a semiconductor

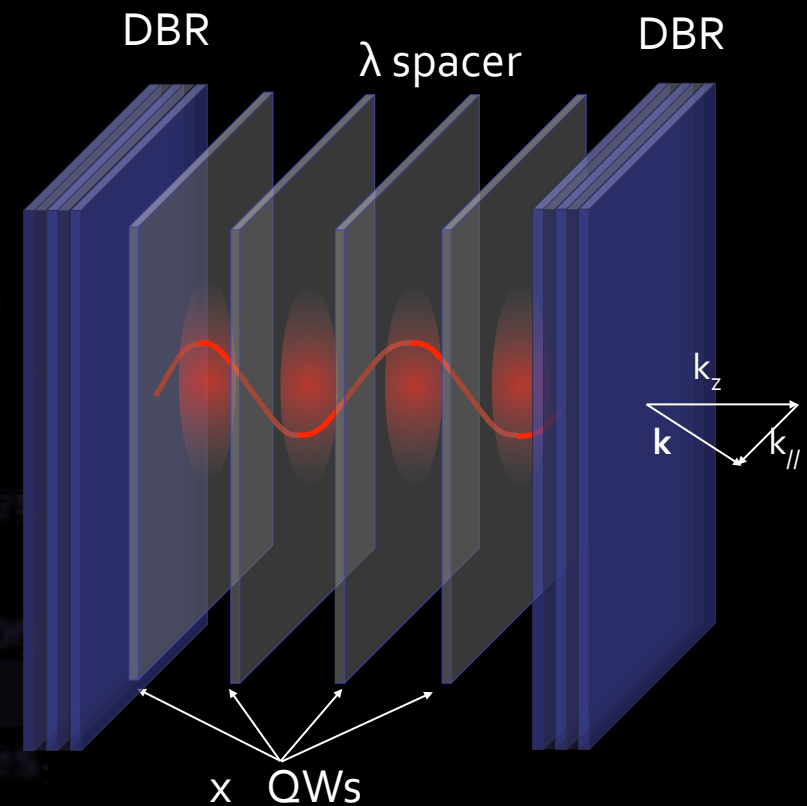


$$= 0,1$$

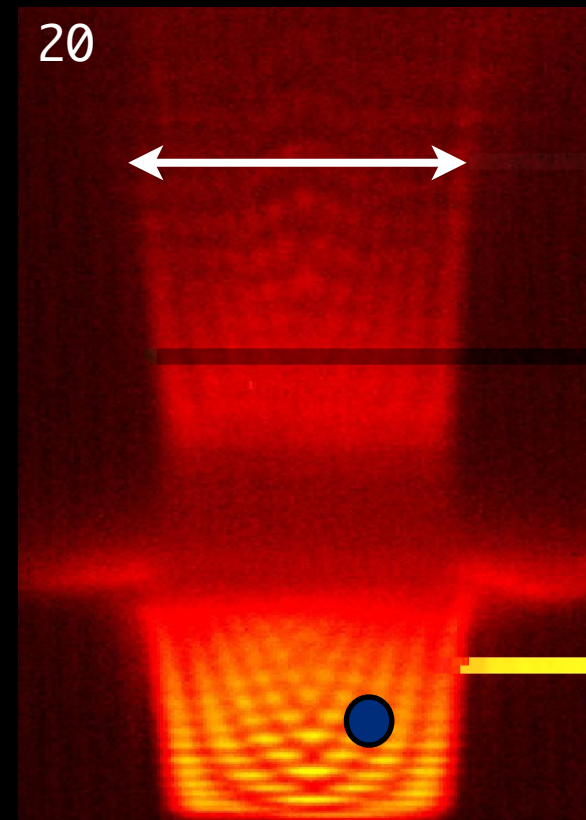
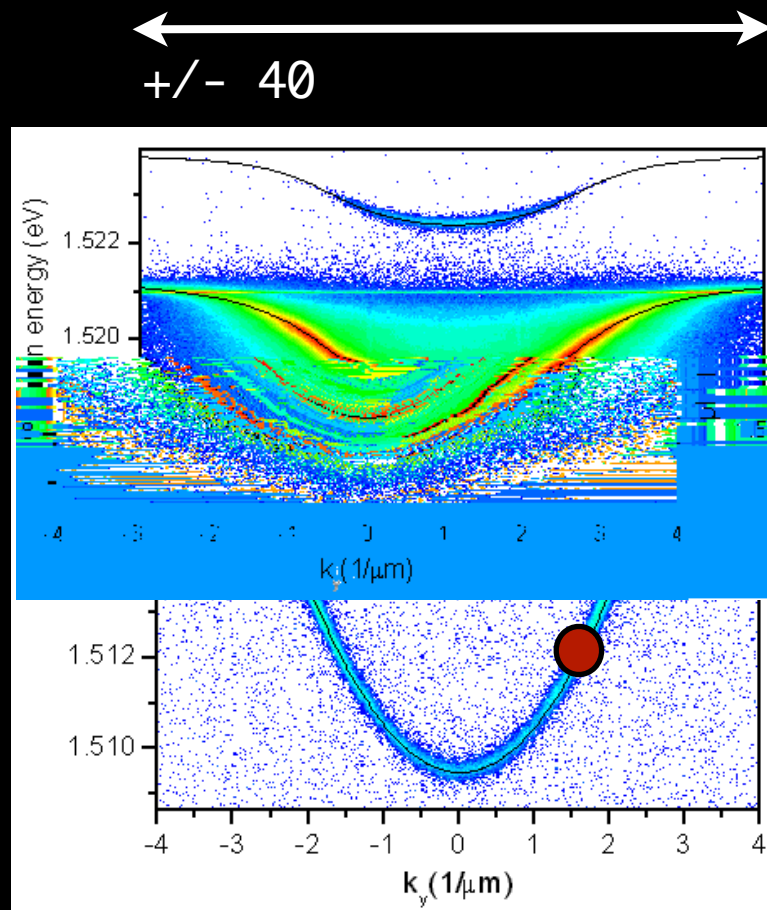


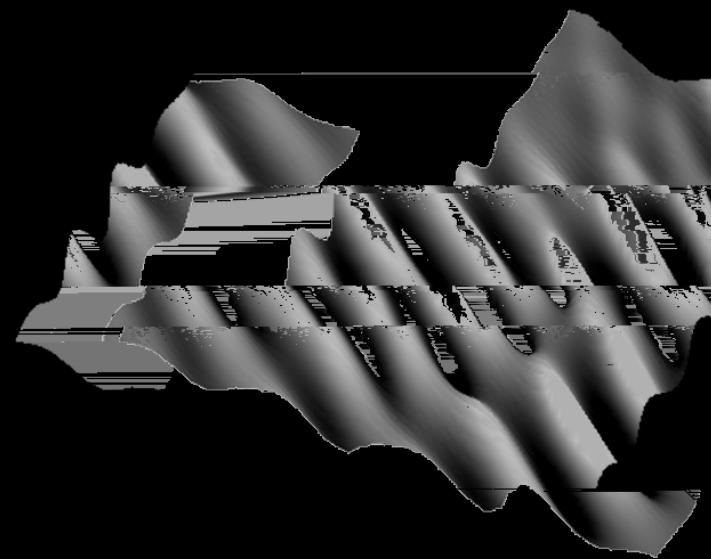
Microcavity polaritons: Half light / half matter particles

- Bosonic particles with a very small mass
- The emitted direction is given by the ratio between the momentum of the photon and the exciton
- The dispersion relation, with the energy of the photon and the exciton
- Energy, momentum, polarization
- Coherence and noise properties



Direct access to the polariton
branch in k-space & real space





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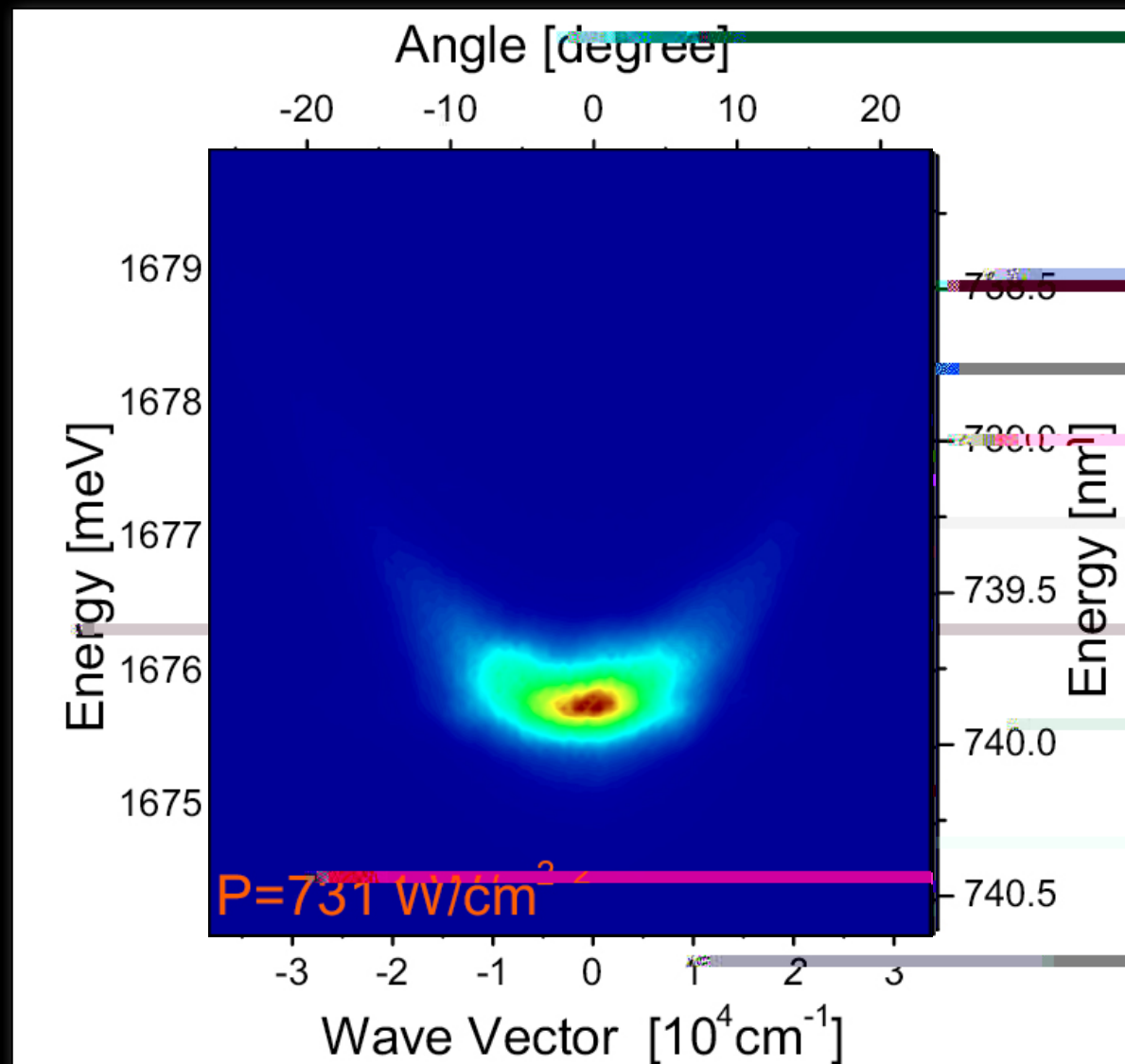


BEC smoking gun



Long Range Spatial Ordering

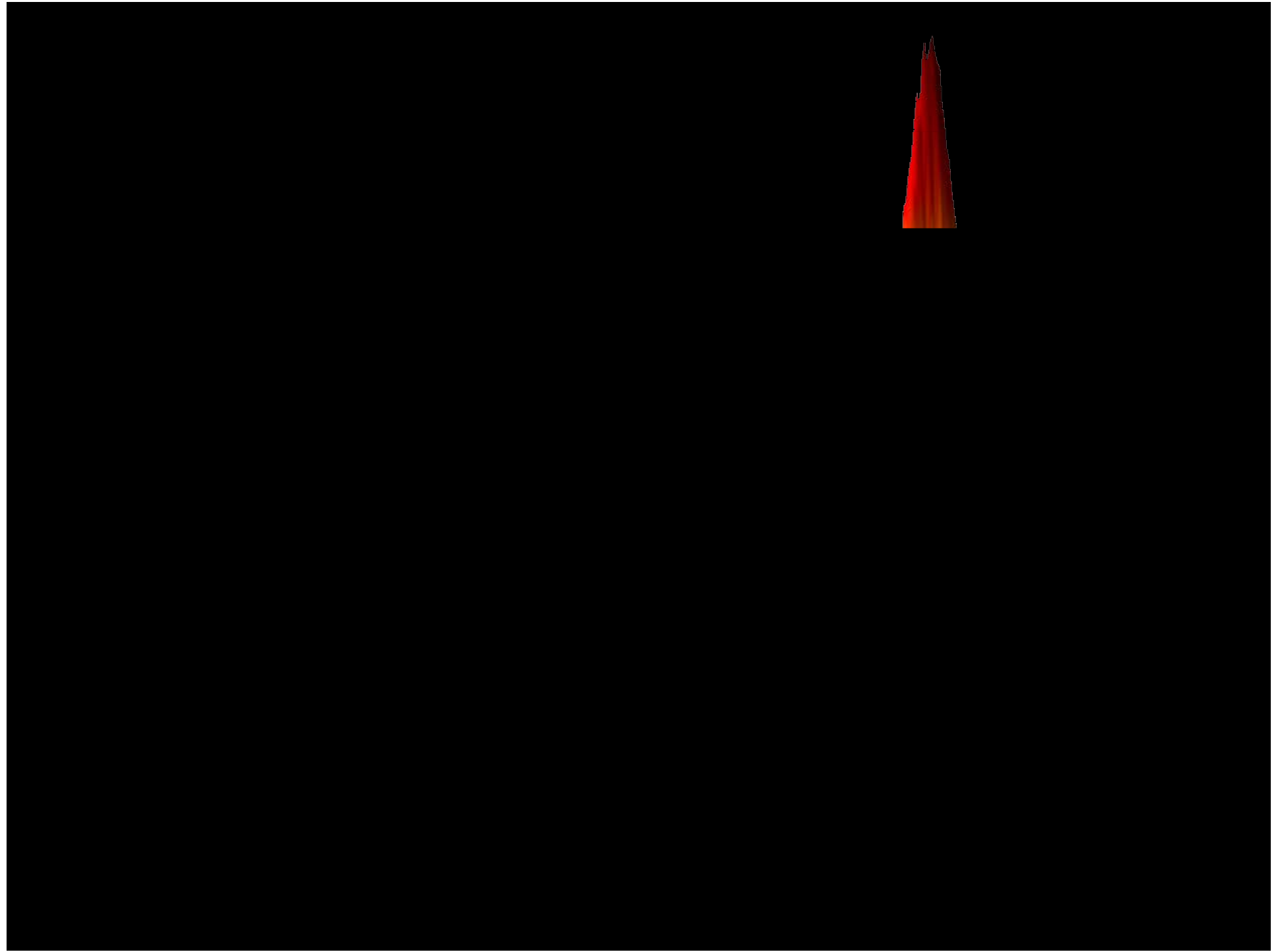
Polariton condensation



From Boltzmann to Bose distribution

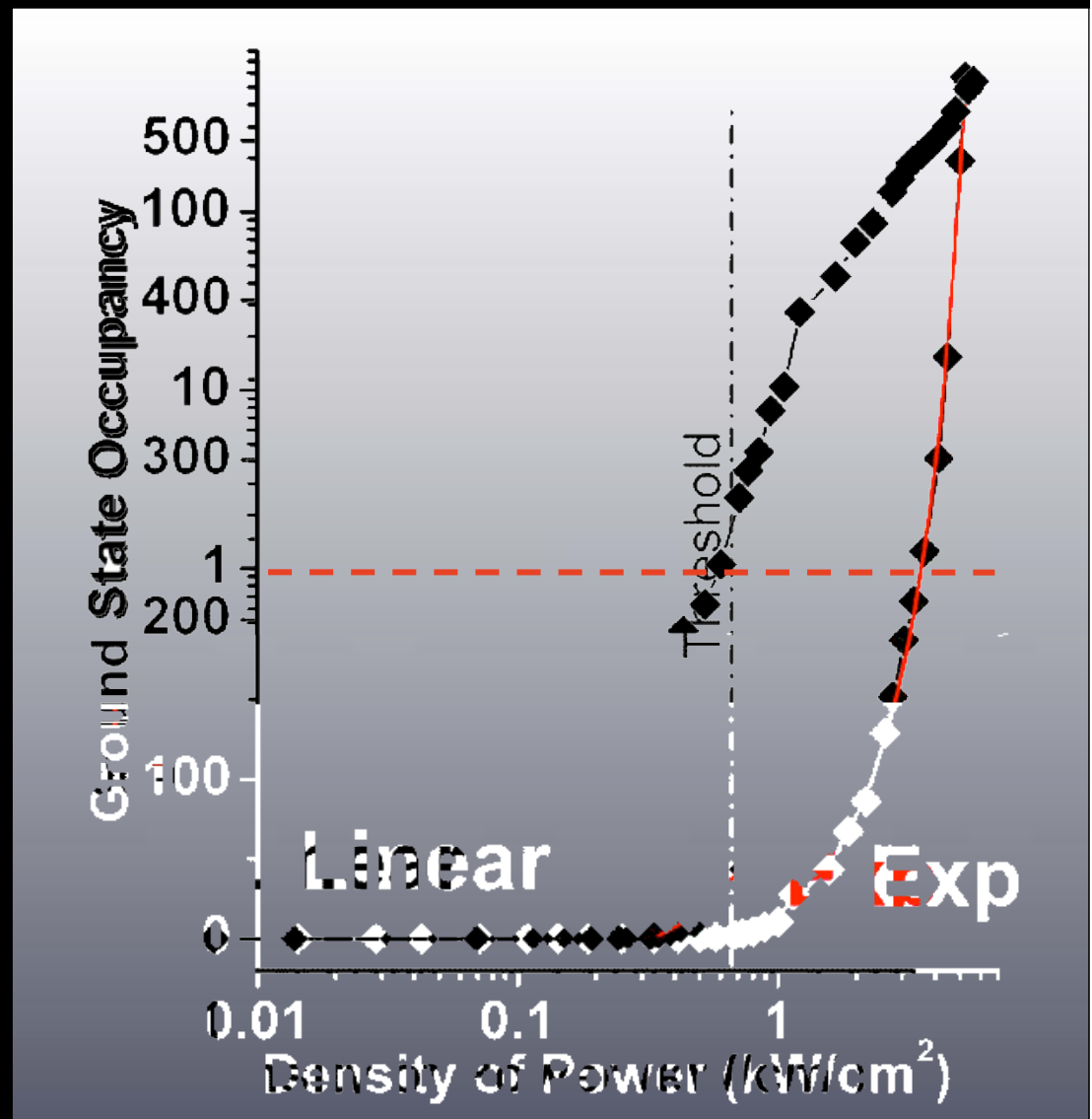
=1

$$100 \left| T_{\text{eff}} = (19 \pm 1) \text{ K} \right. \quad \rho/\rho_c$$



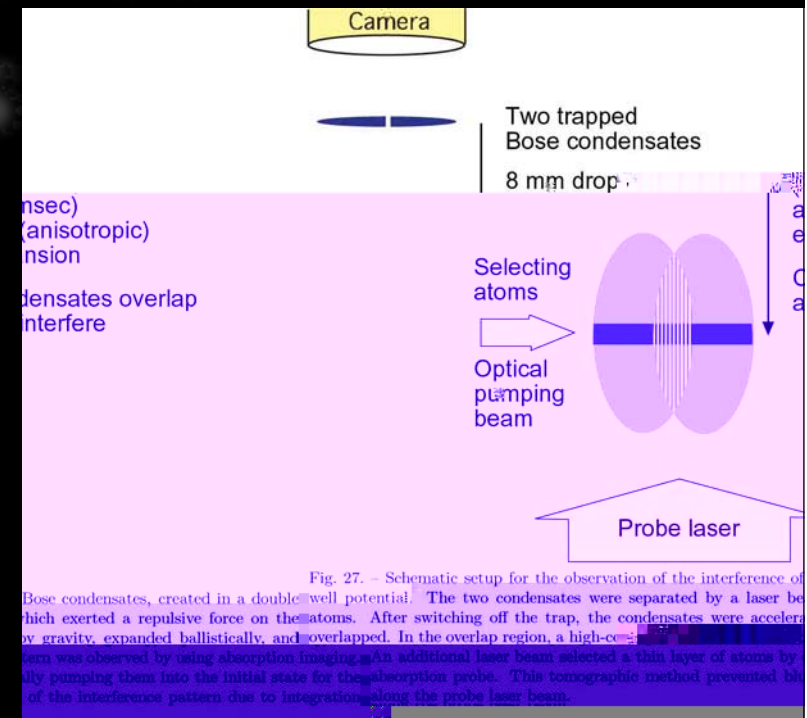
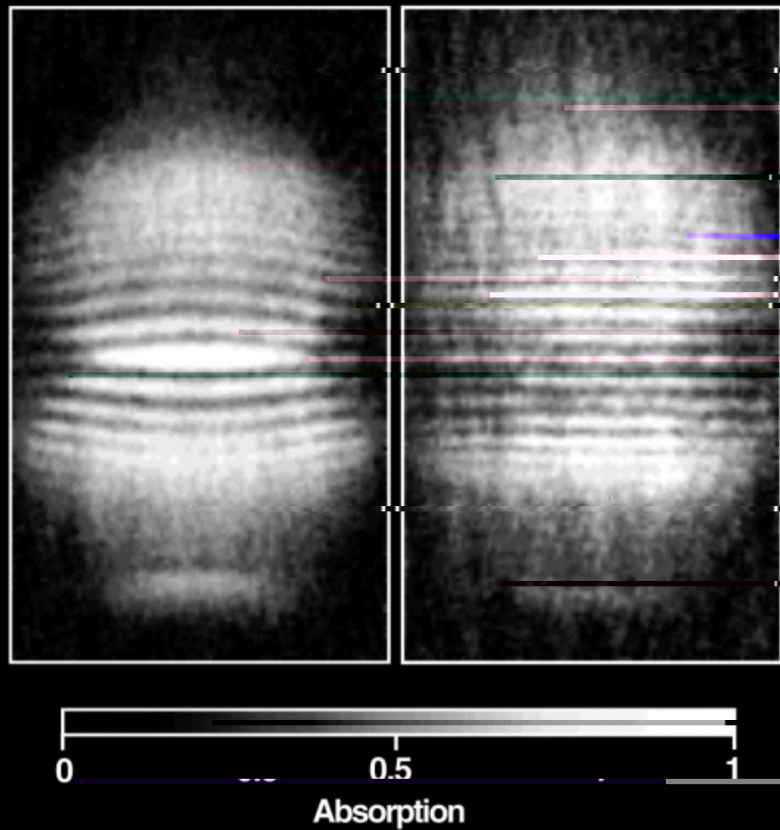
Clear condensation threshold

= 1



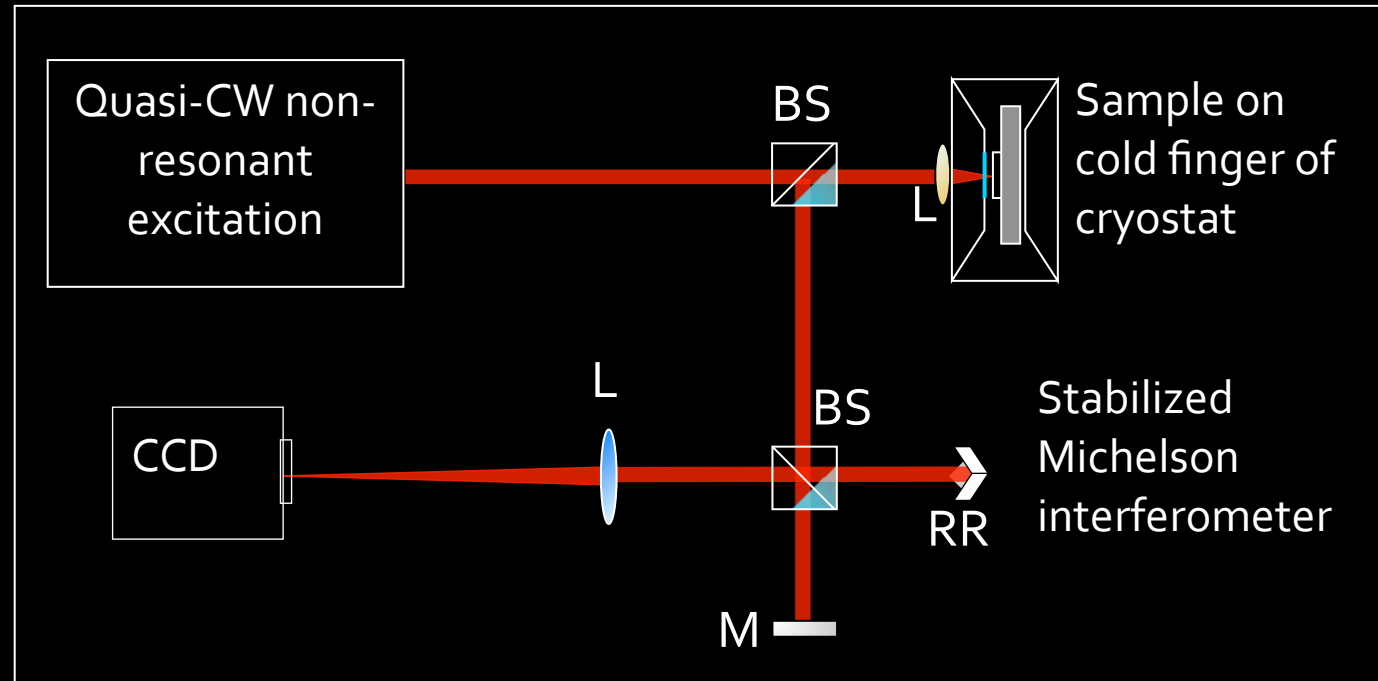
Interferences between condensates

2

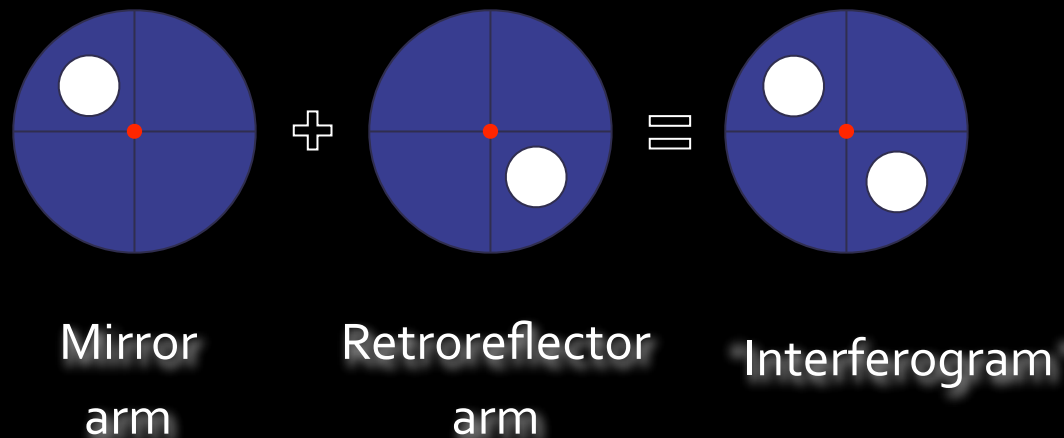


Ketterle et al, 2001

● Setup:



● Principle:





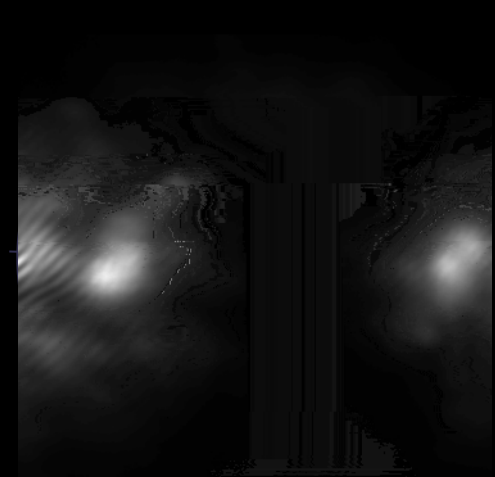
Mirror arm

+

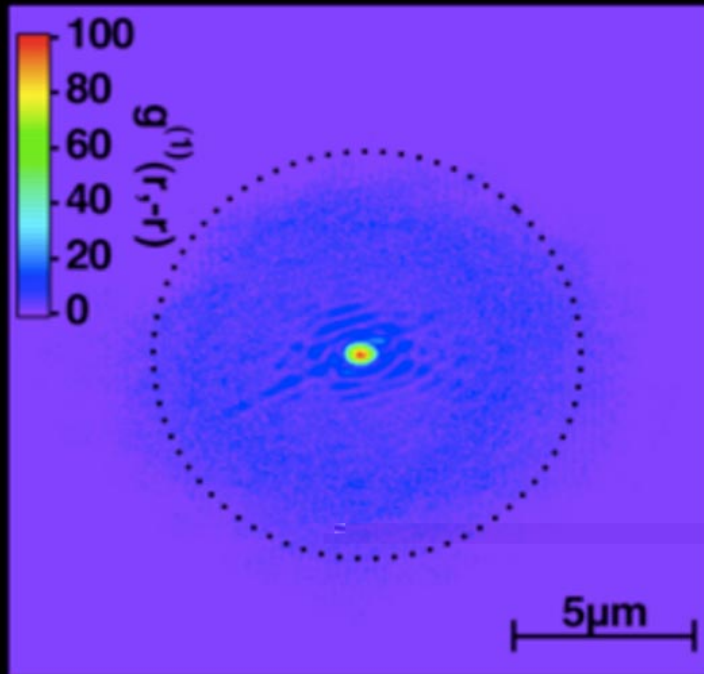


Retroreflector
arm

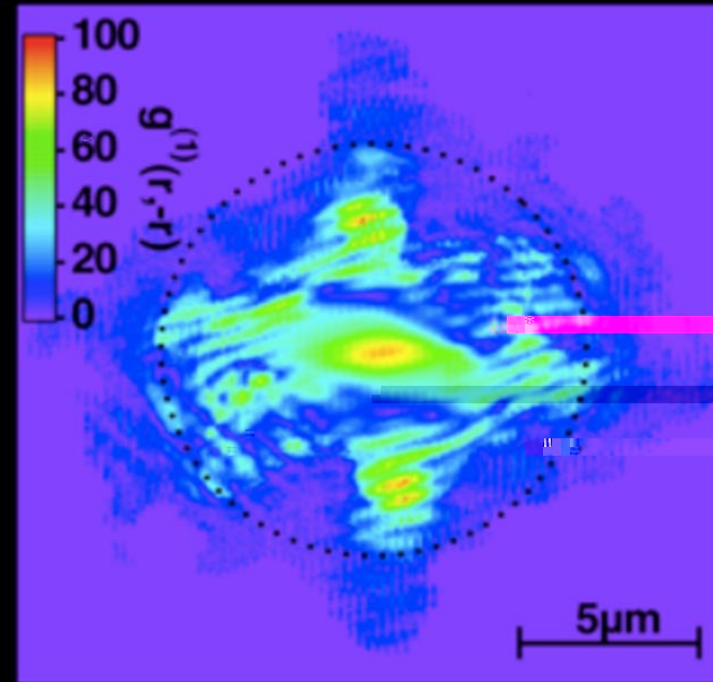
=



Interferogram



Below threshold,
De Broglie WL of the polariton

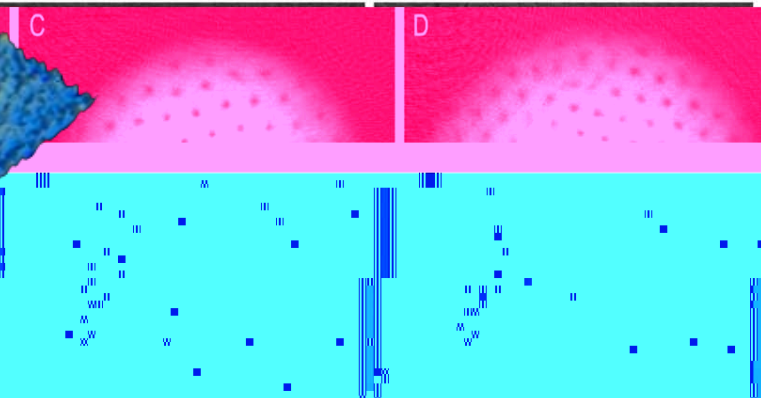
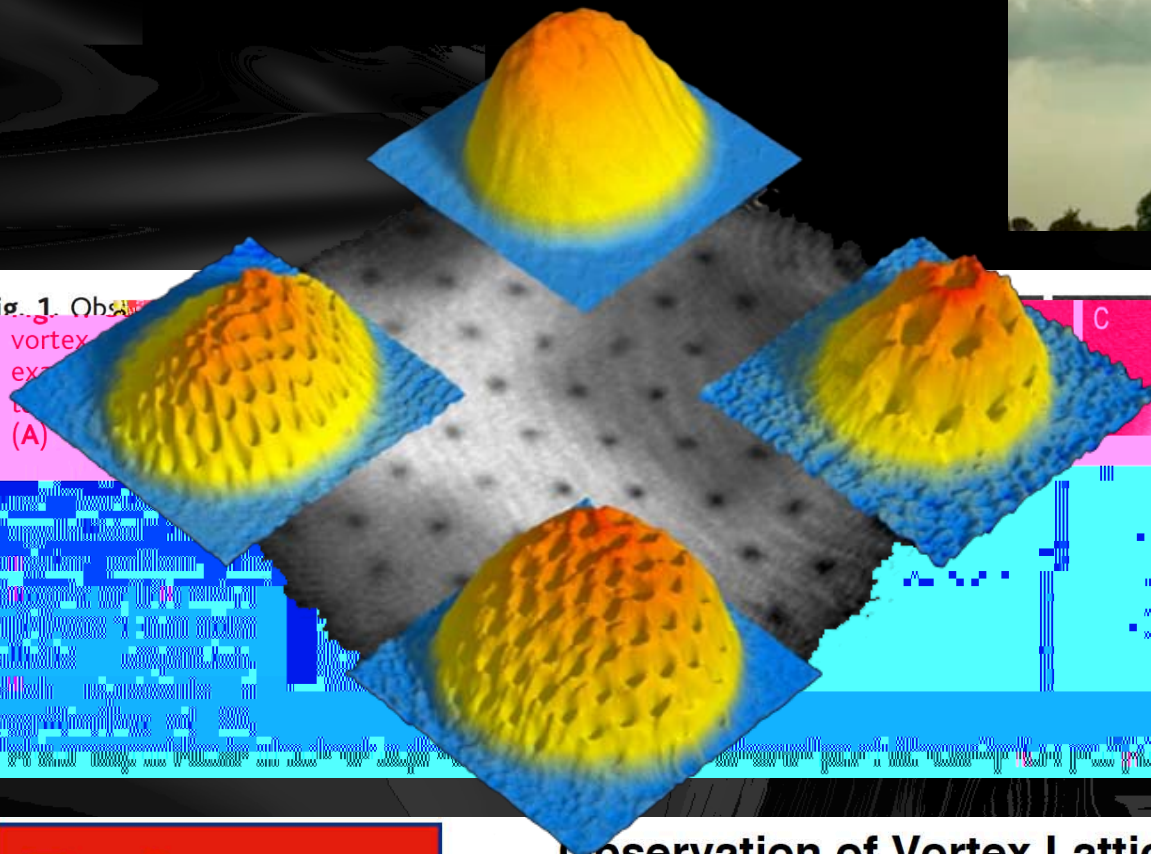


Above threshold,
Long range ordering

! " # \$ % & ' ' (') * +
 , - (+ . / % 0 1 \$ 2



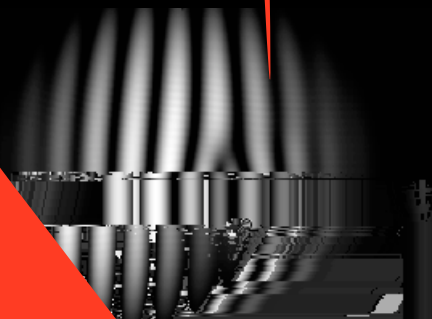
Fig. 1. Observed
 vortex
 ex
 (A)

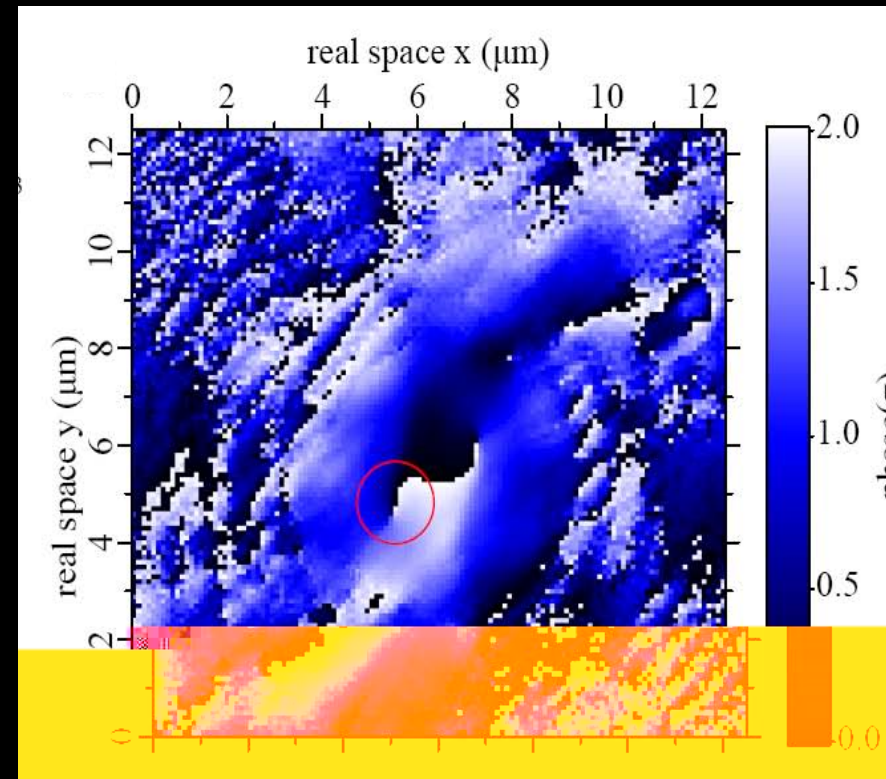
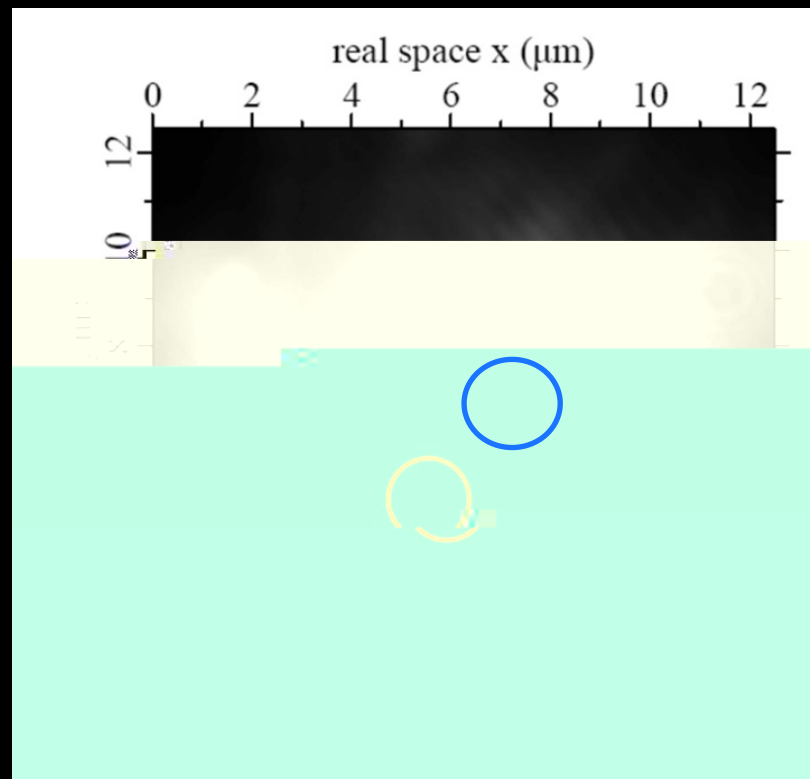


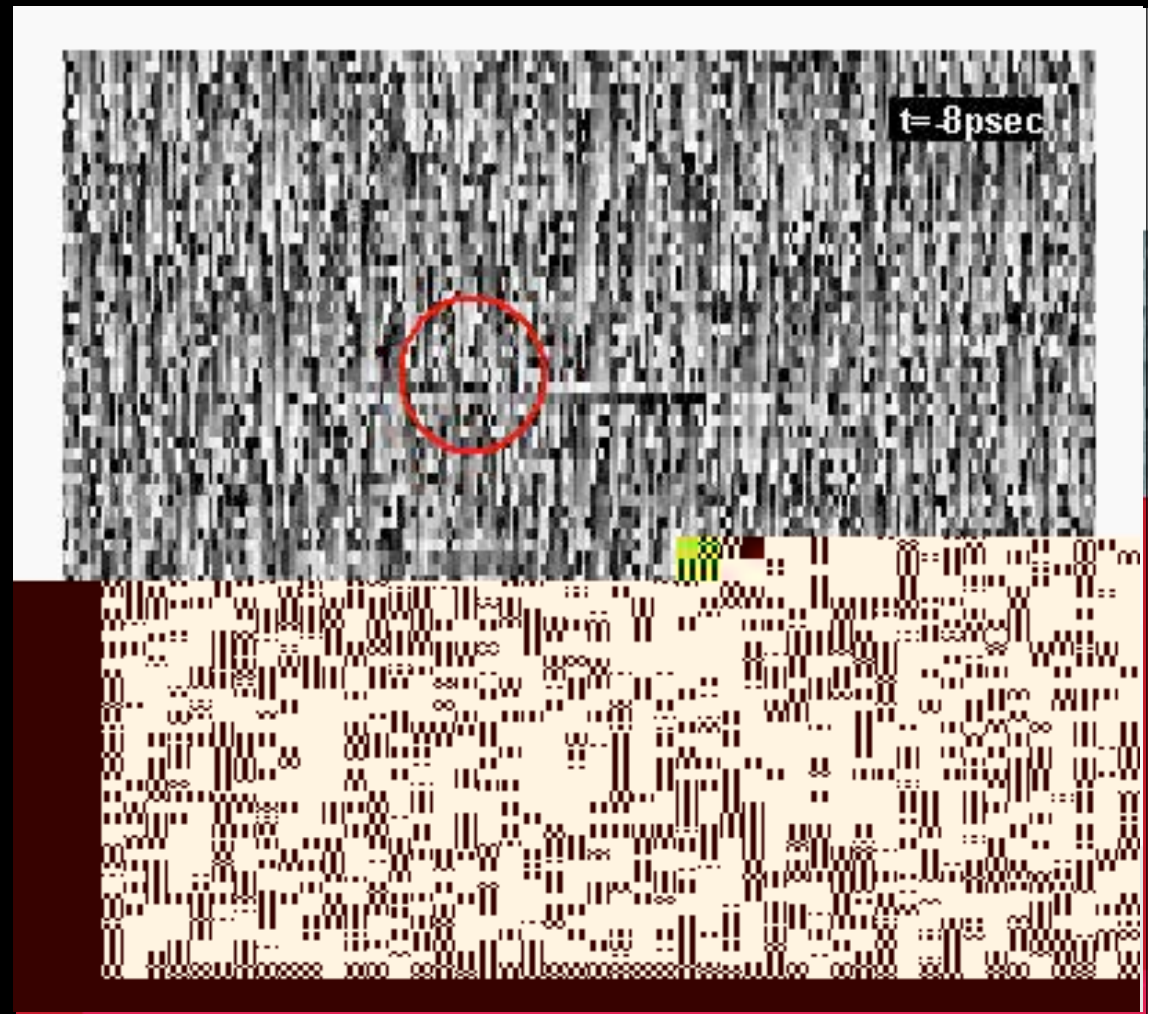
Conservation of Vortex Lattices in Bose-Einstein Condensates

Kettune et

2!





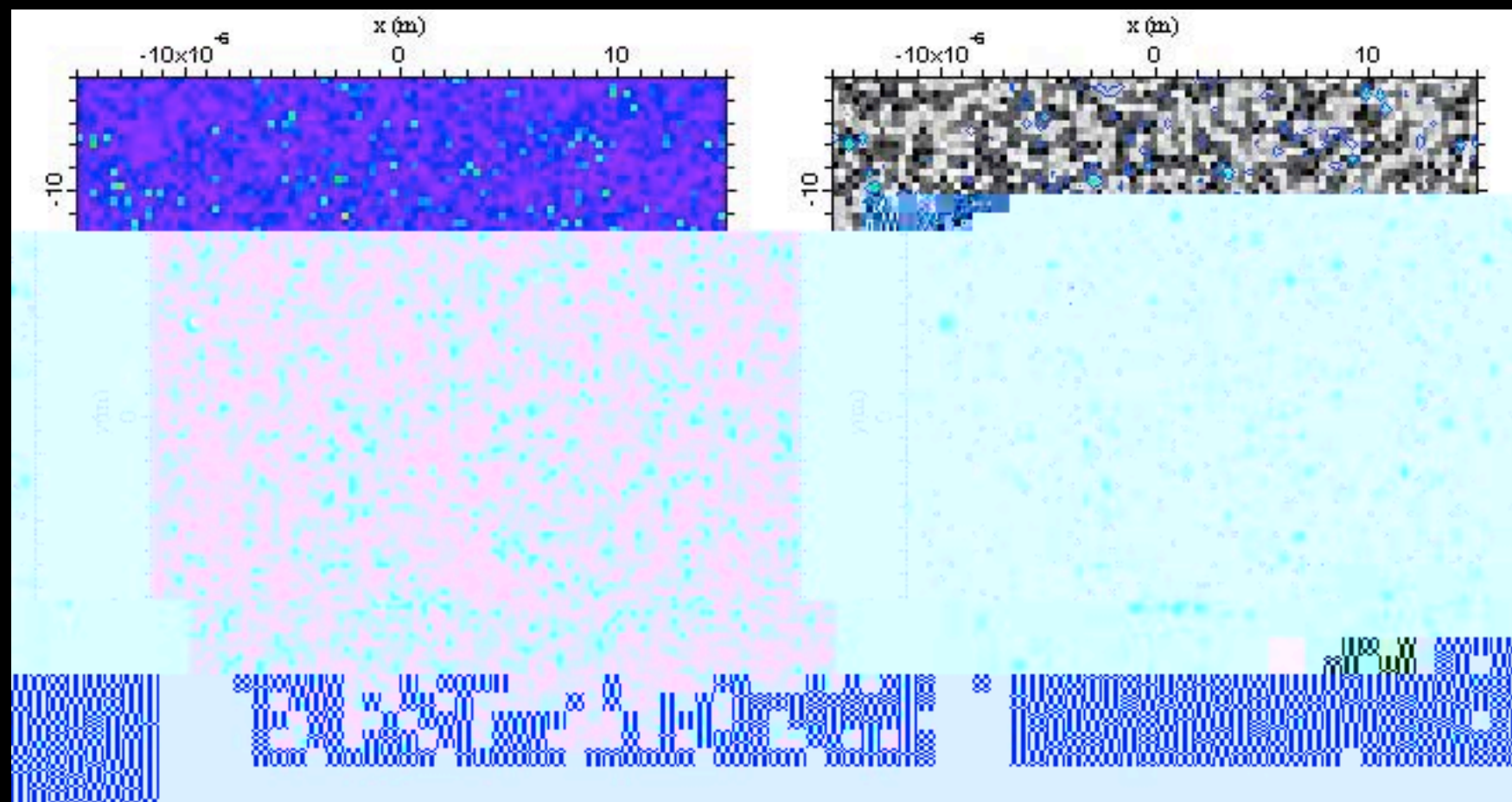


Physical Review Letters

moving physics forward

Reconstructed Time resolved Real space interferences

Lagoudakis et al., PRL , ()



-

., +



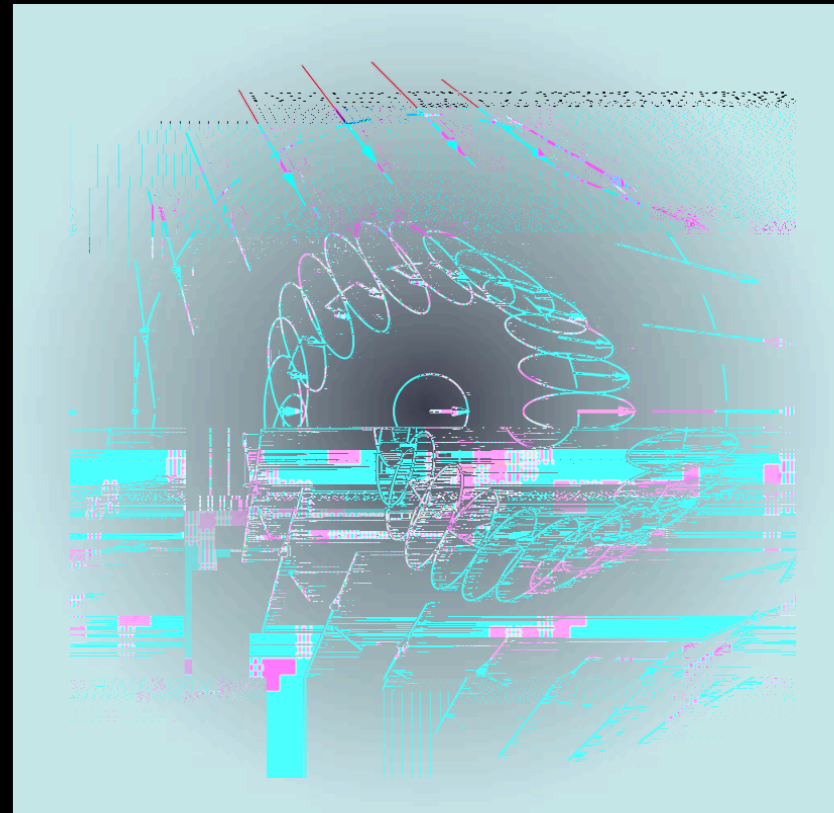
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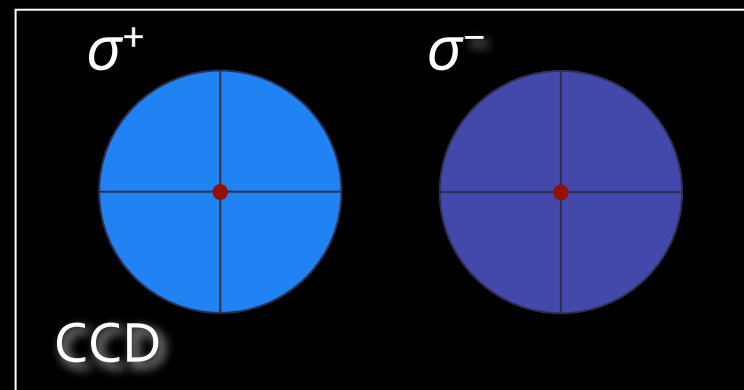
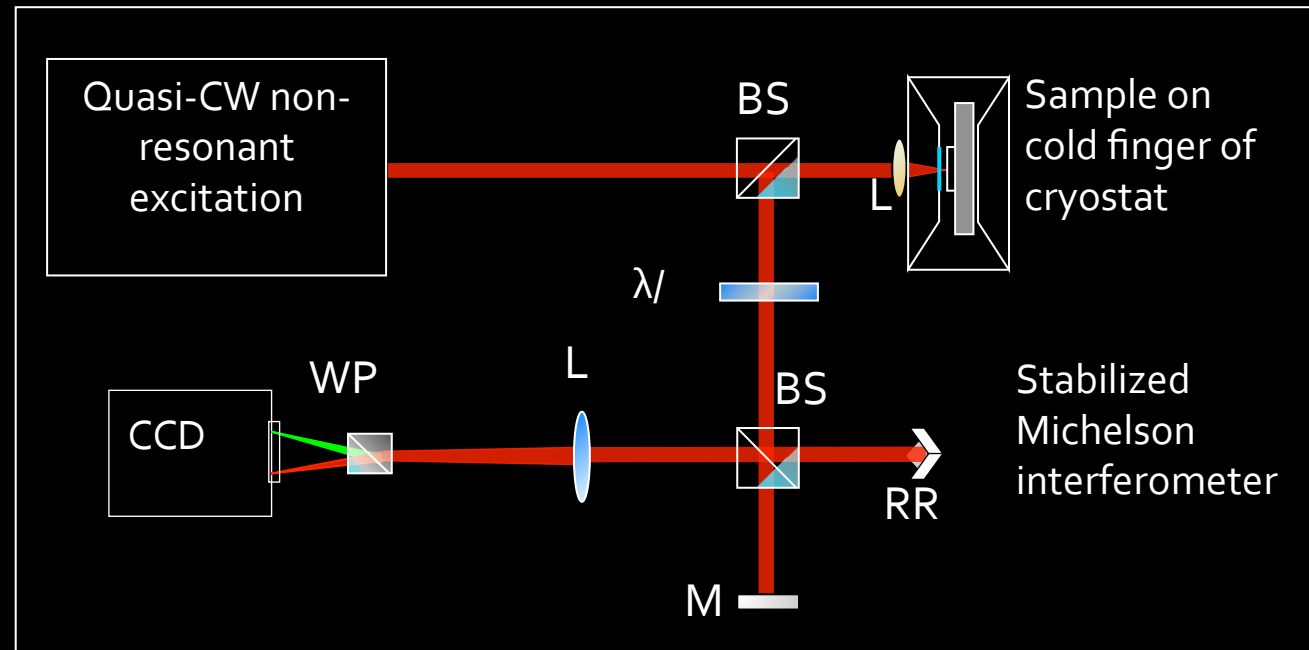


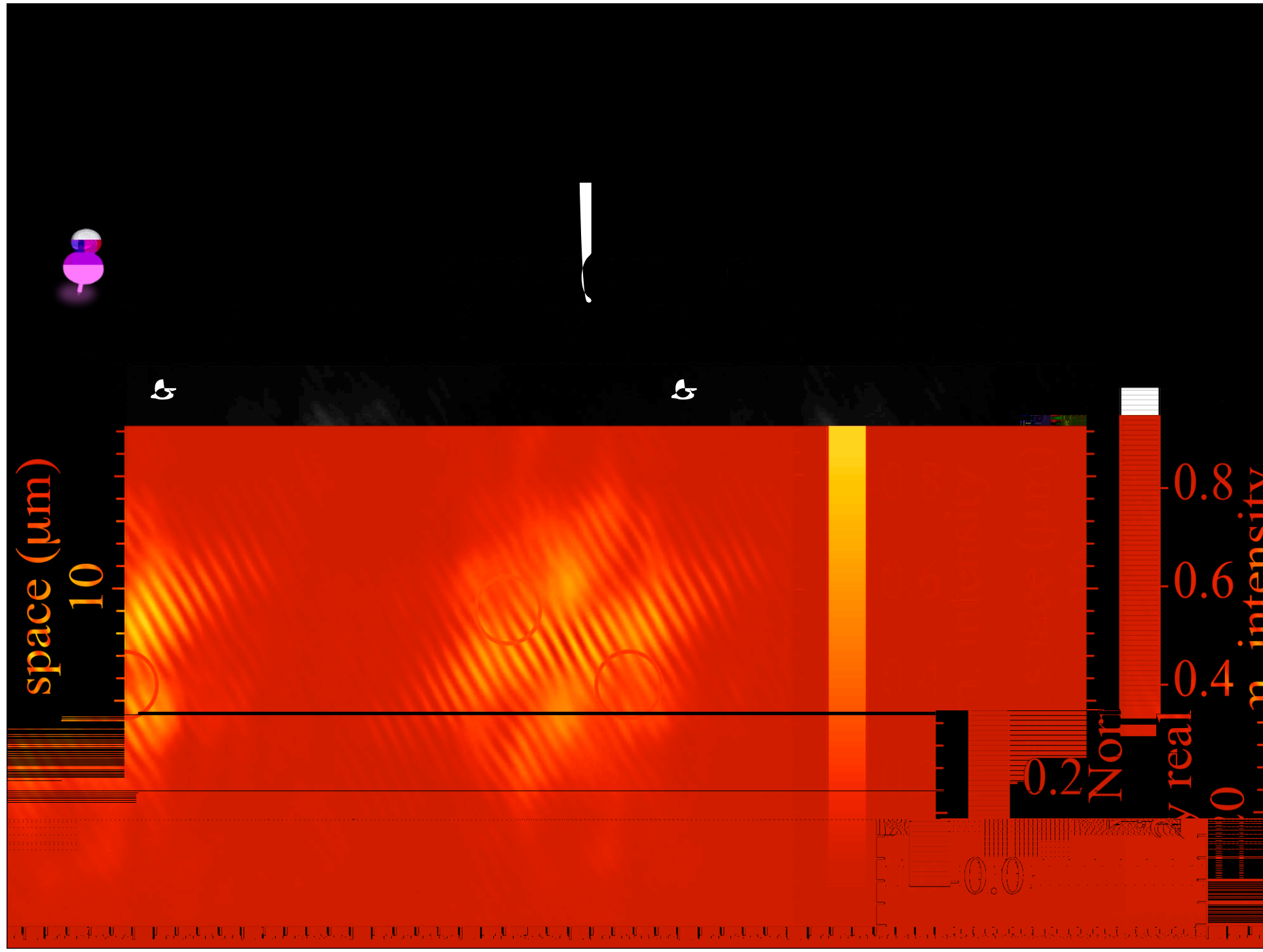
How would a half vortex look like?

Physical Review Letters

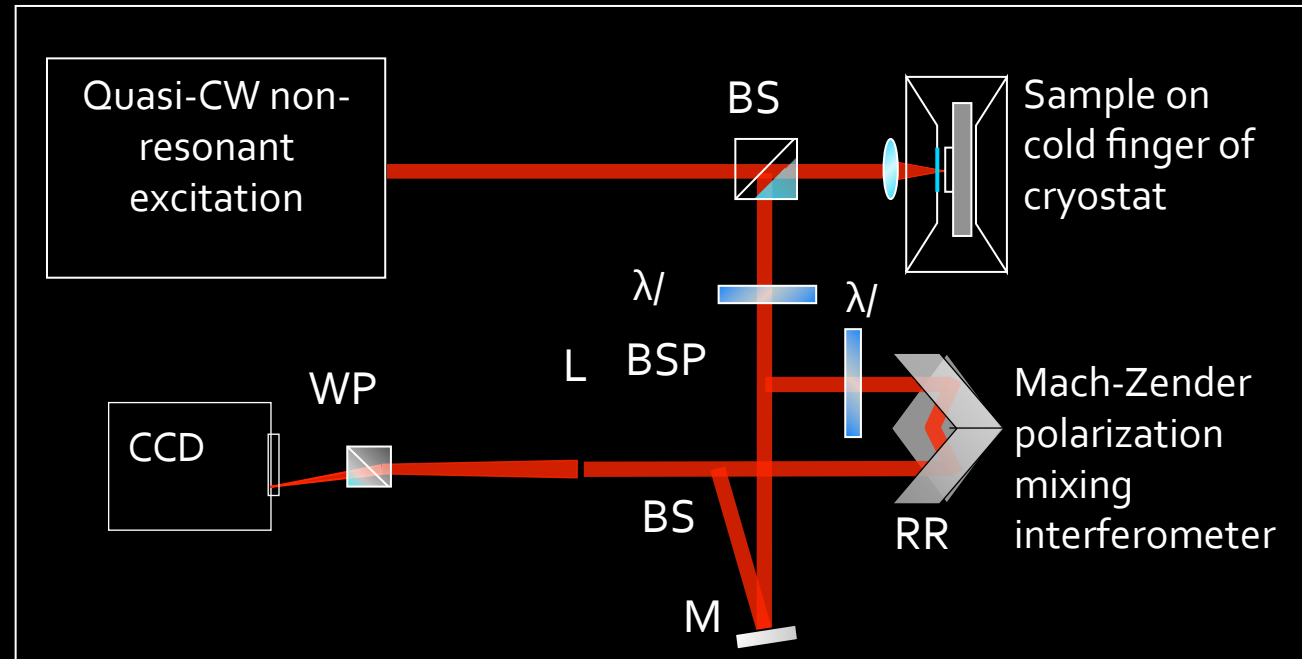
moving physics forward

Yuri Rubo, *Phys. Rev. Lett.*, ()

σ^+ σ'' 



$$\sigma^+ - \sigma''$$

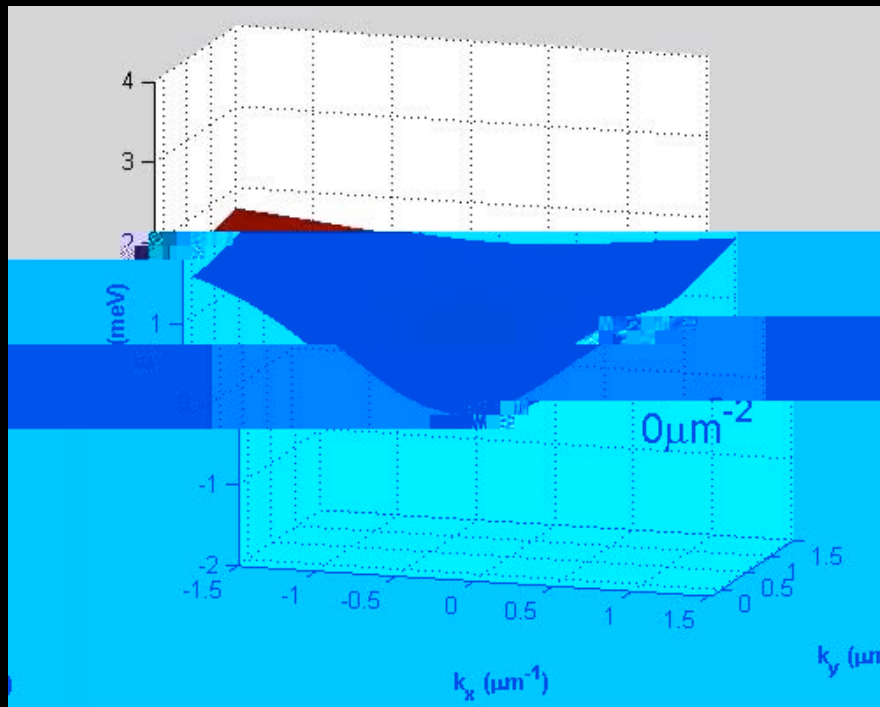


Superfluidity and Bogoliubov excitations

- Consequences of superfluidity
- Linearization of the dispersion
- Appearance of a ghost branch



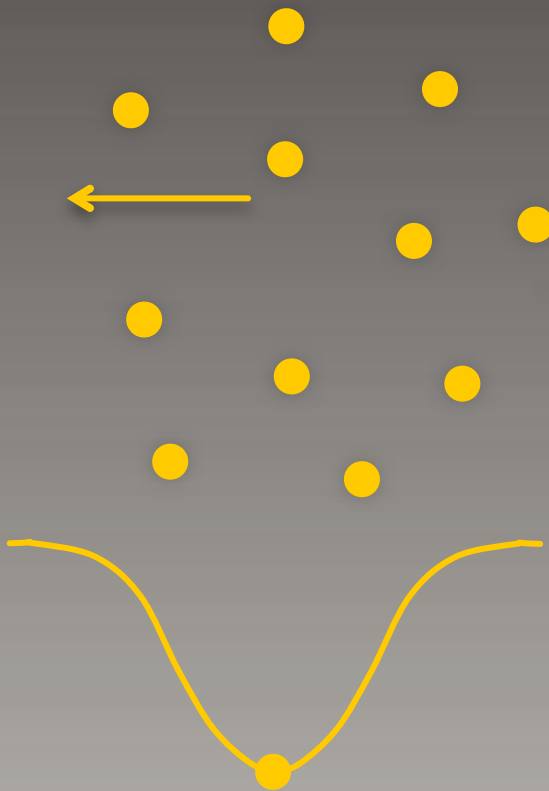
Superfluid Helium fountain



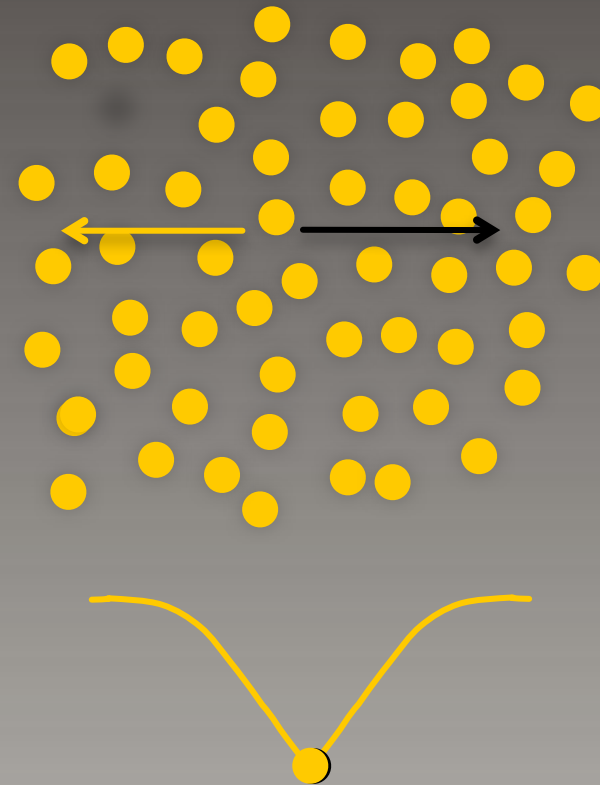
N. N. Bogoliubov.
On the theory of superfluidity.
J. Phys. (USSR), ()

Naive picture of the ghost branch

Diluted polariton gas



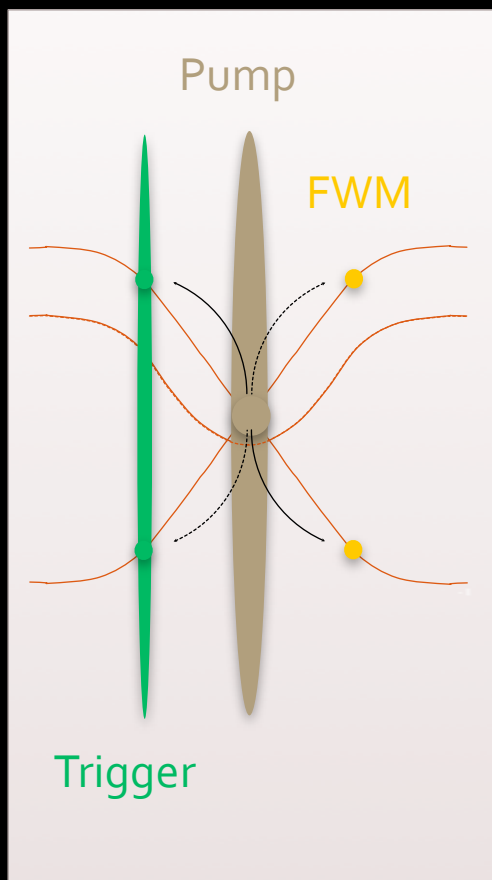
Sound wave in superfluid



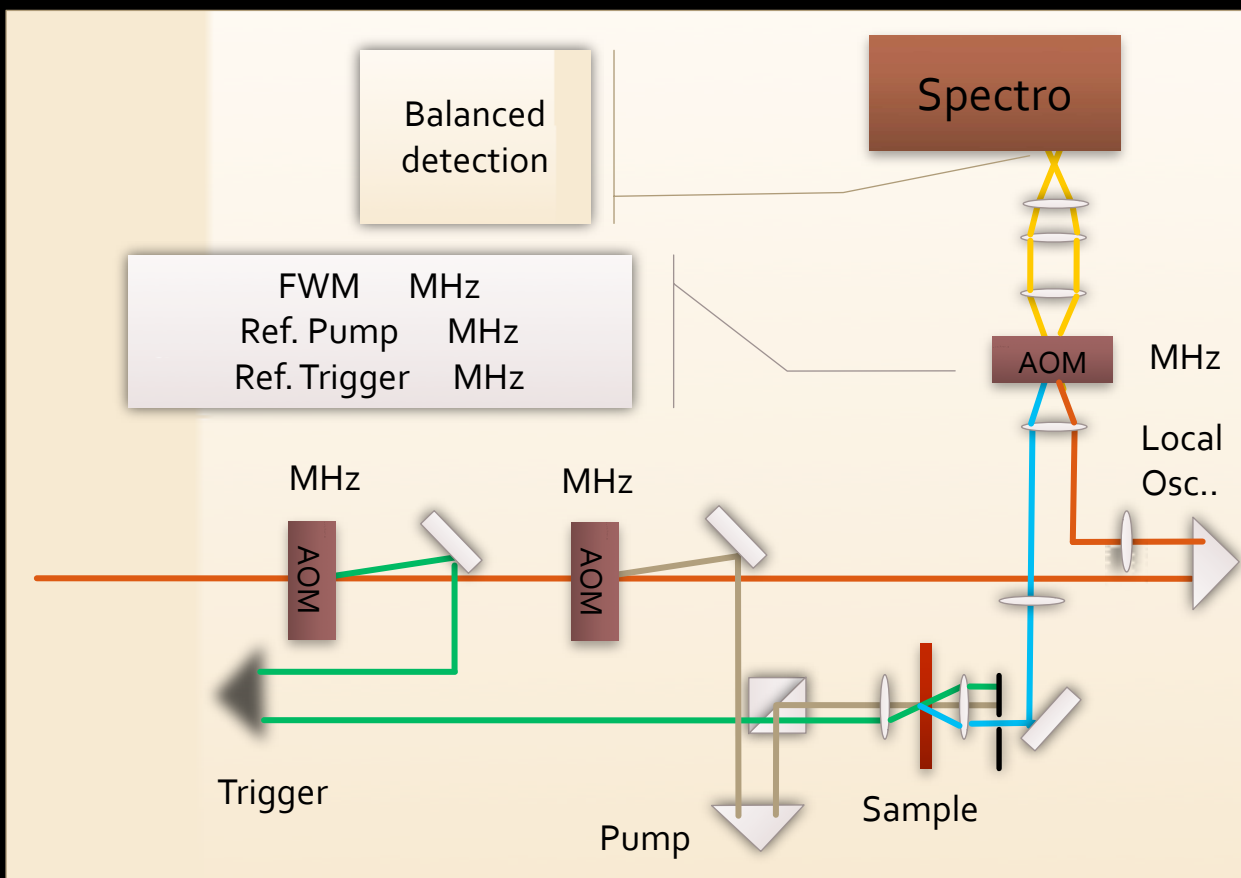
Particle-hole superposition

Coherent excitation

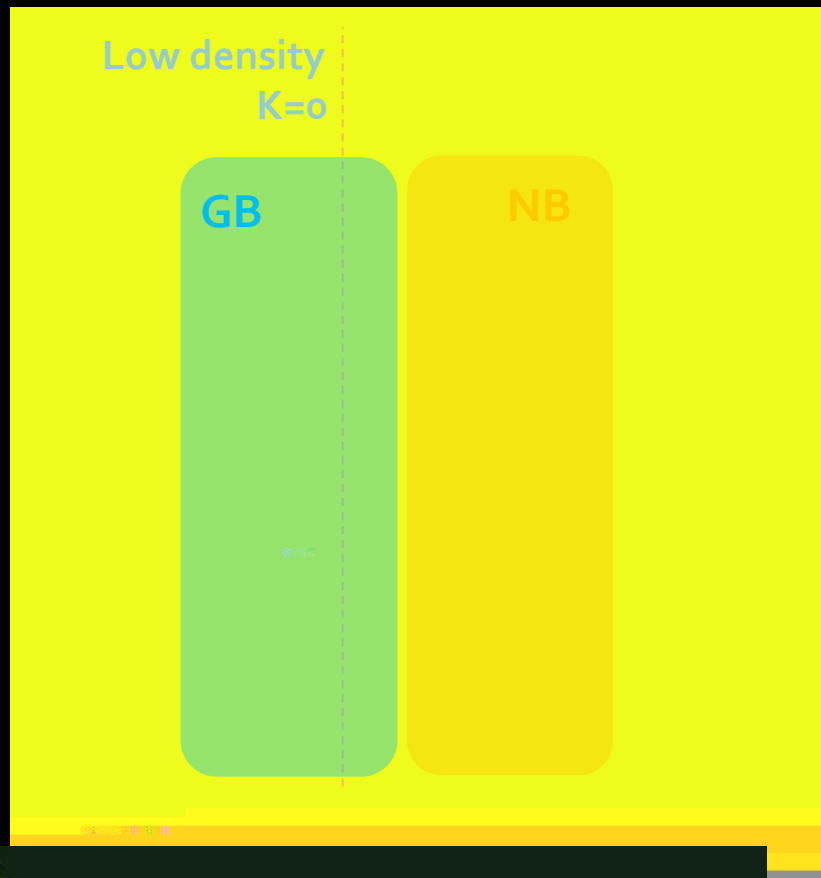
Pulsed resonant excitation



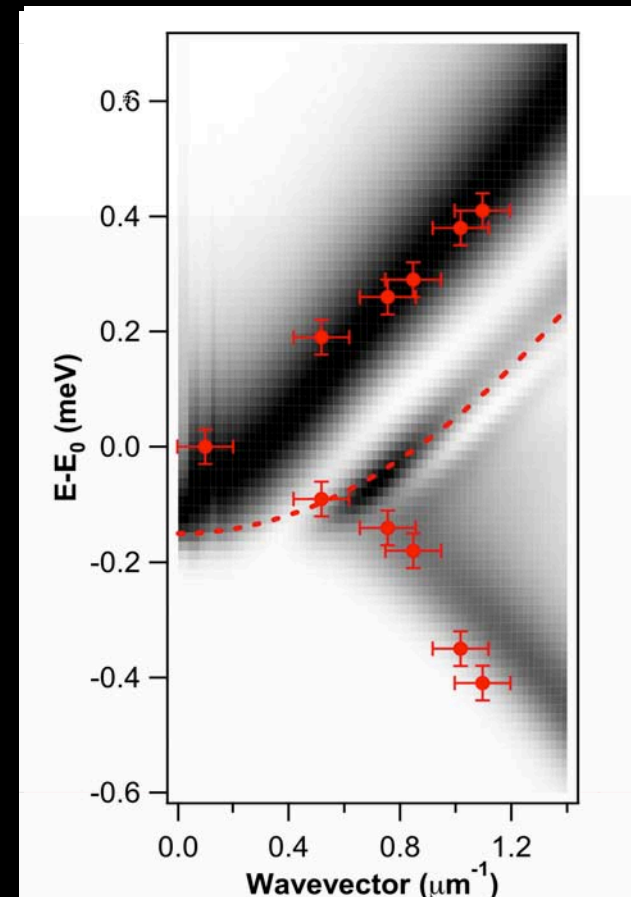
Spectral interferometry Energy selection



Normal & ghost branch



Damping of polariton density!



Physical Review Letters
moving physics forward

Kohnle et al, *Phys. Rev. Lett.* ()

How to observe superfluidity? not only Ghosts



Superfluidity and Critical Velocities in Nonequilibrium Bose-Einstein Condensates

Michiel Wouters¹ and Iacopo Carusotto²

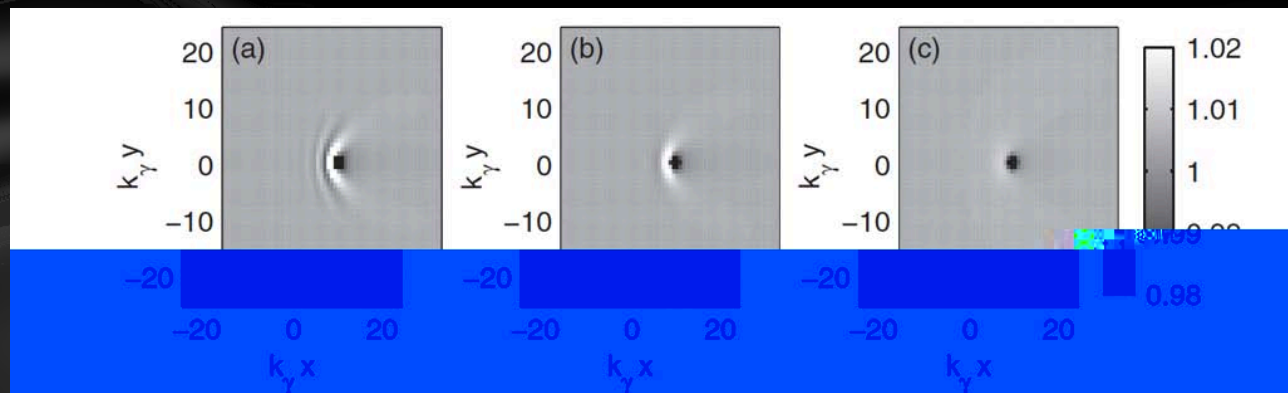
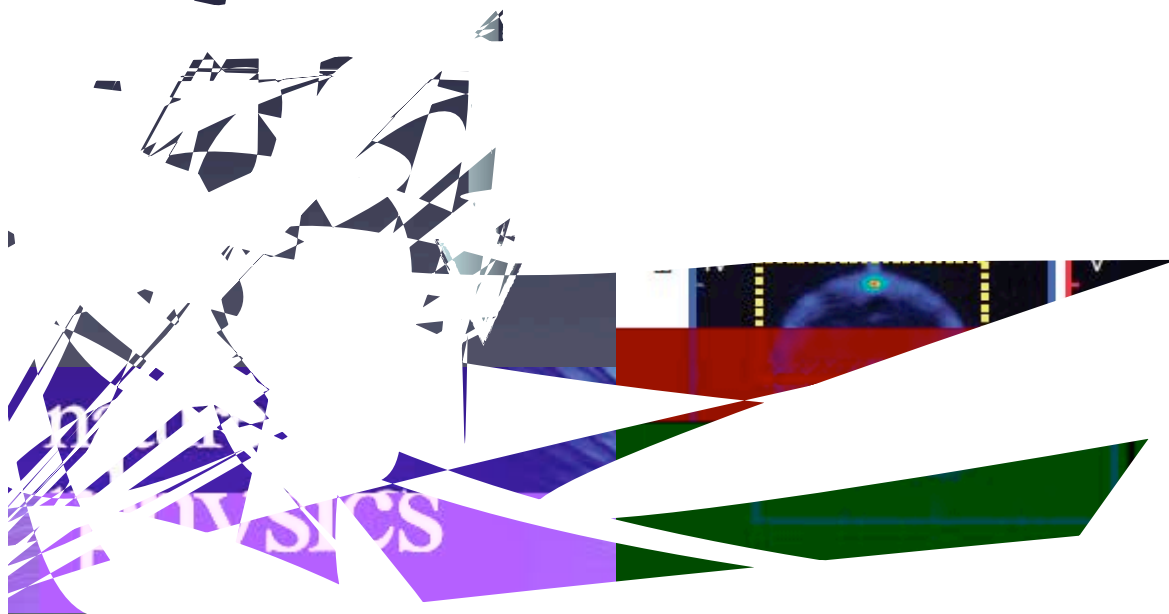
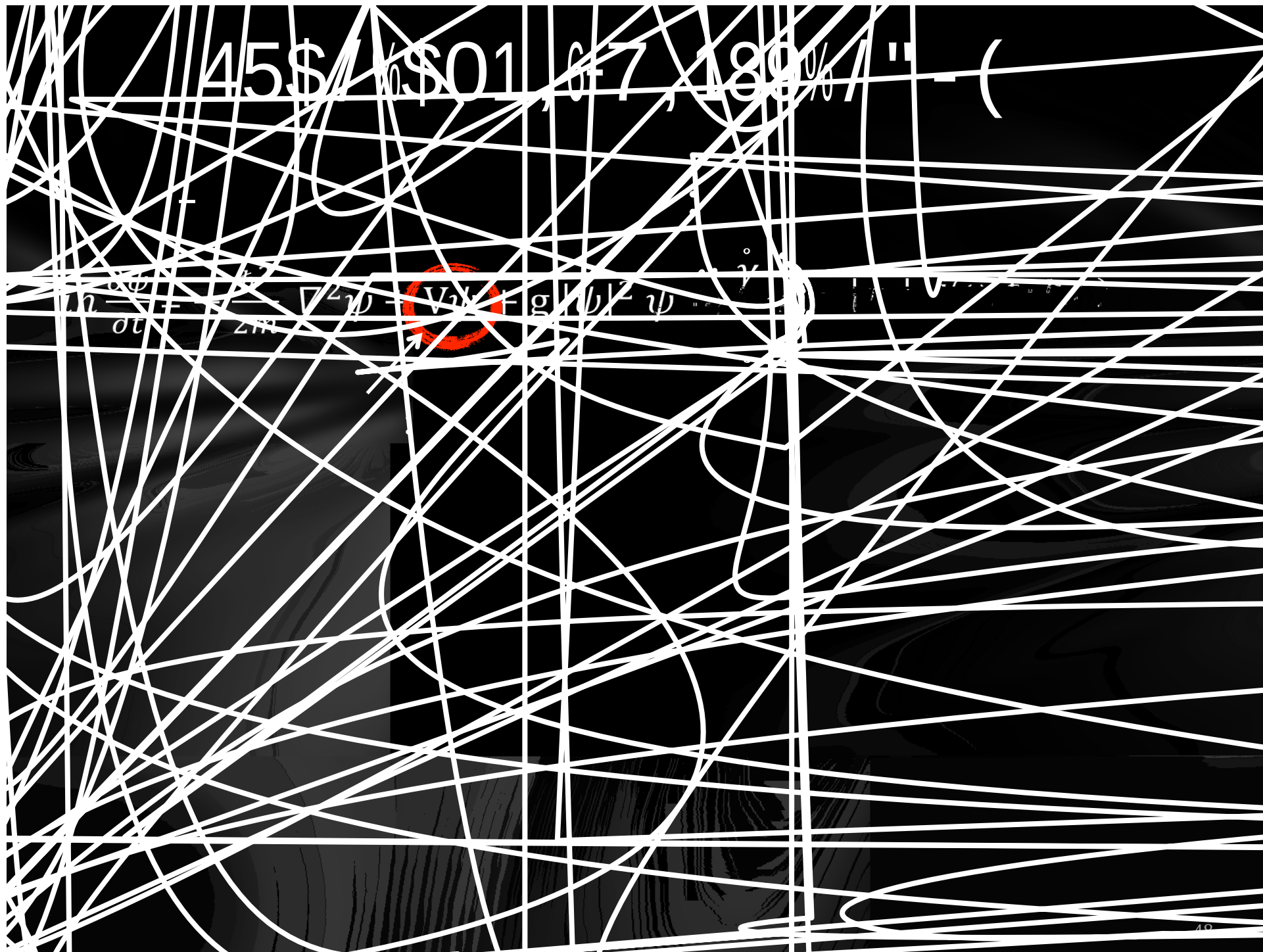
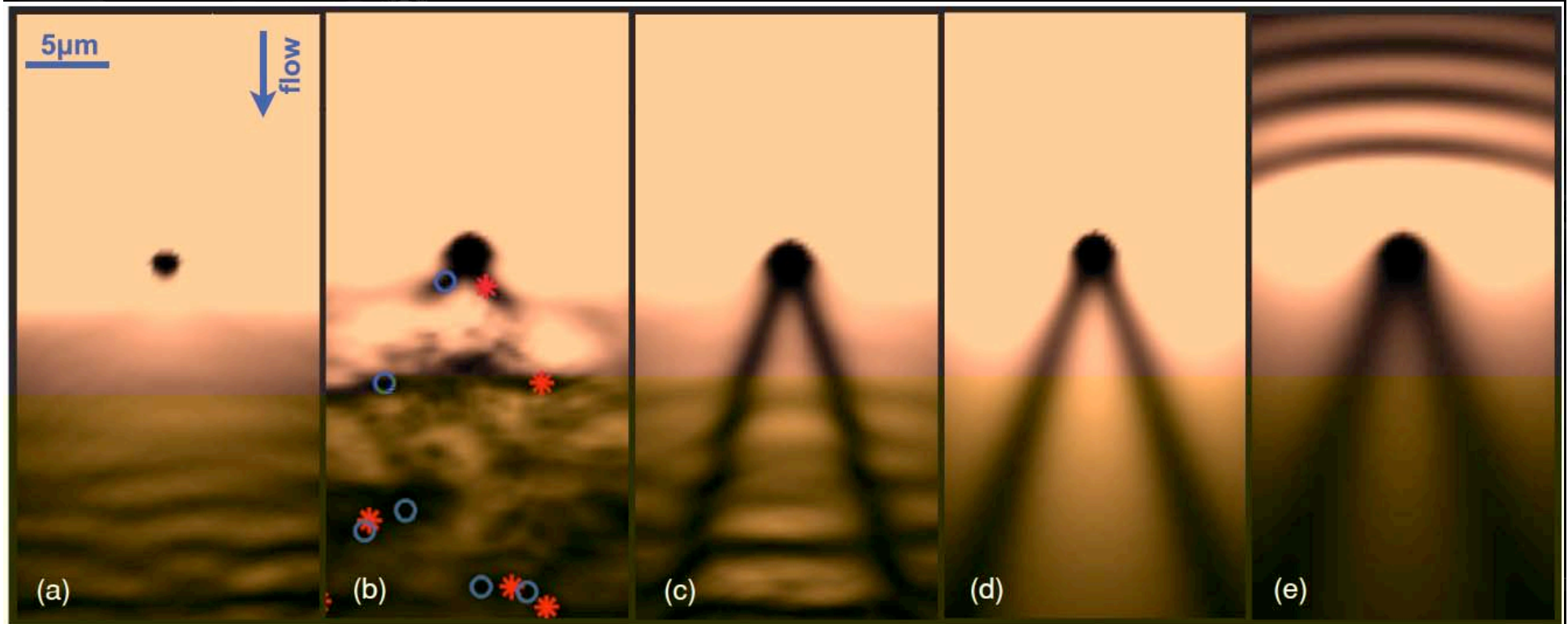


FIG. 3. Density perturbation created in a moving condensate by a stationary weak defect for three values of the condensate velocity $v/c_s = 1.5, 1, 0.4$ across the critical value for superfluidity. Parameters: $n_c g/\gamma = n_c r/\gamma = 1$, $\Omega_K/\gamma = 50$.





$$: * (\% / (* - , 3 '12+ / ; + \# / 6 , \%') / - + \& "' (2$$



Physical Review B

condensed matter and materials physics

Pigeon et al, PRB, , ()

$<, \%8+2/6') / -2+' - +\#/6, \%') / - +\&' '(2$

Science **Polariton Superfluids Reveal Quantum Hydrodynamic Solitons**
 A. Amo *et al.*
 DOI: 10.1126/science.1274800
 1274800, DOI: 10.1126/science.1274800

A Amo et al.

[illegible]



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2&\$3%&\$3\$31)%.,\$')-.&0,-)

- !"#45"3-)"6))3"3#\$3,&'),74&5"3-)

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi + g|\psi|^2 \psi$$

- 8,-4#%)6'"2)%.,)/"20,3-&5"3)9,%*, ,3))%.,):\$-0,'-\$+,)&3:)
\$3%, '&/5"3)%,'2-

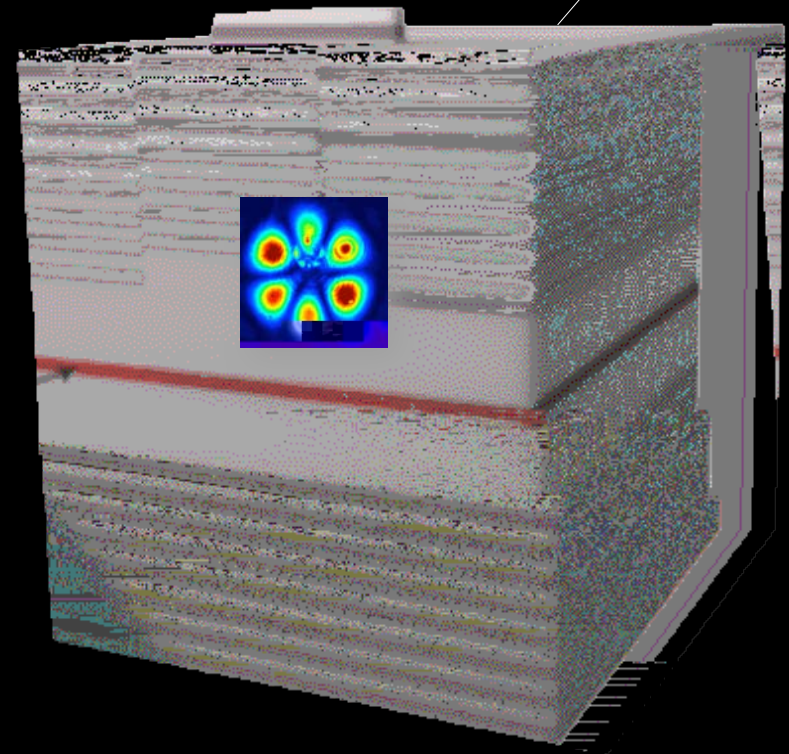
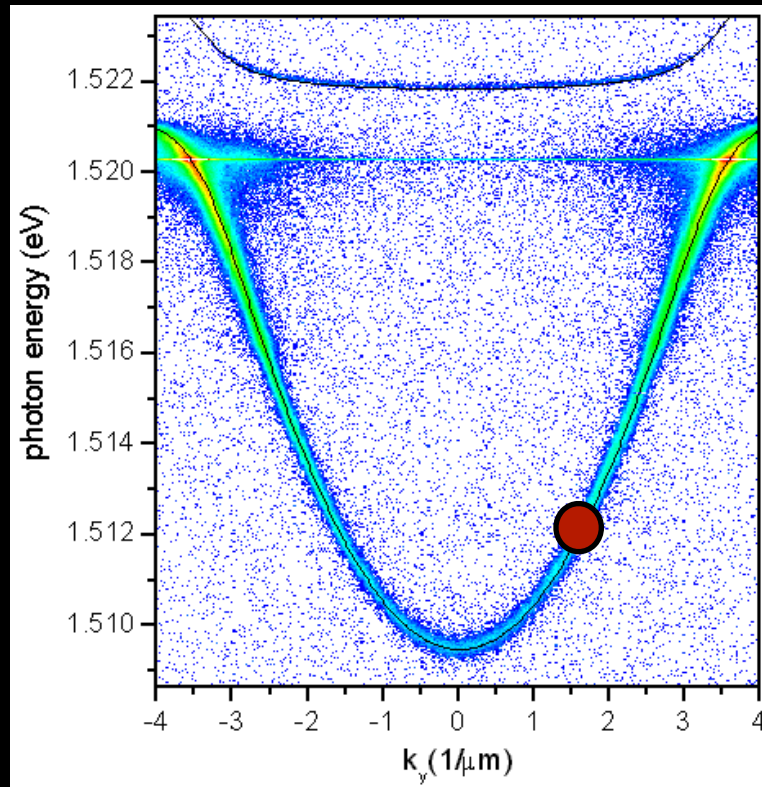
Repulsive interaction $g > 0 \implies$ DARK SOLITONS



))))))))))
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$$=6'''(+.\$6/1')^*$$

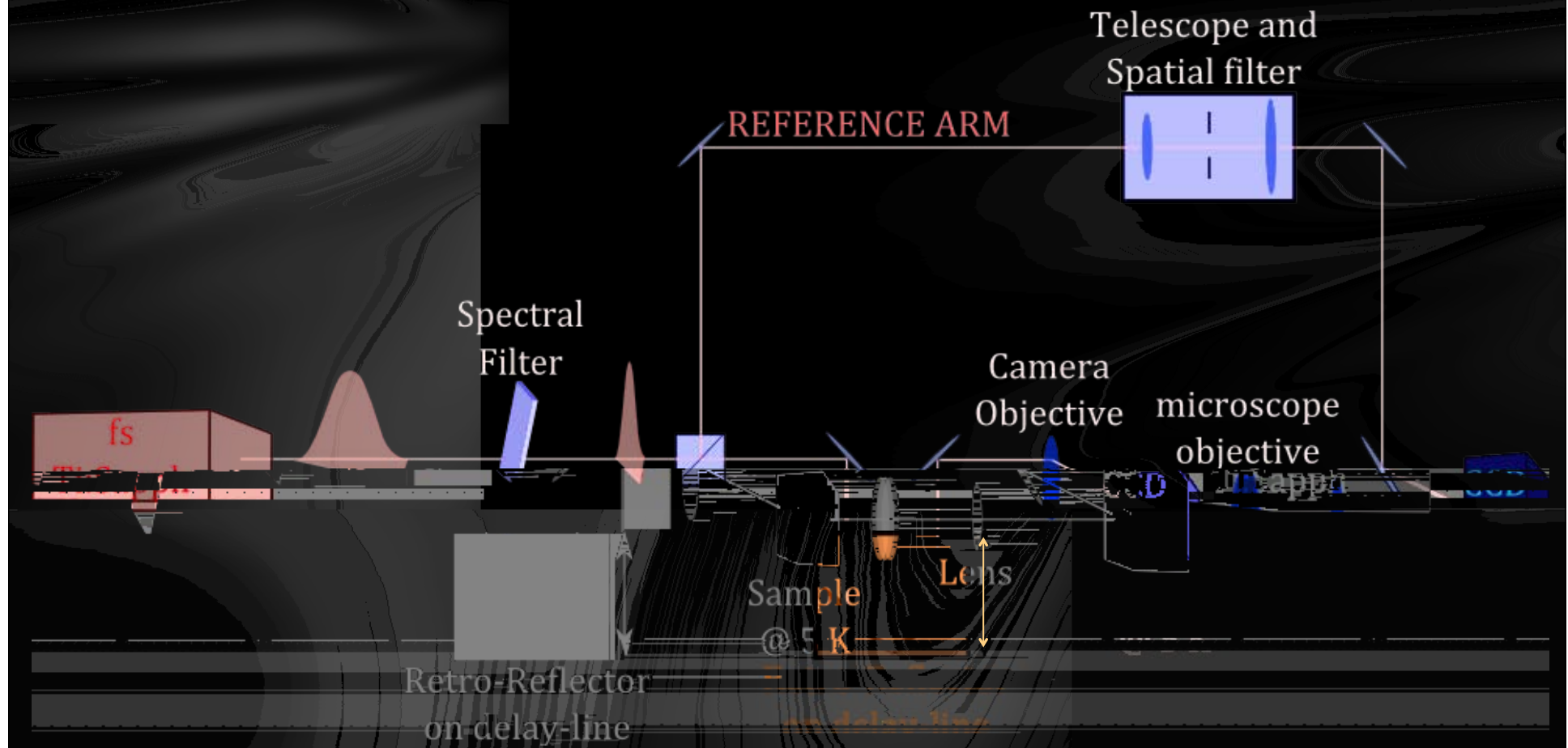
How do we probe this dynamically?



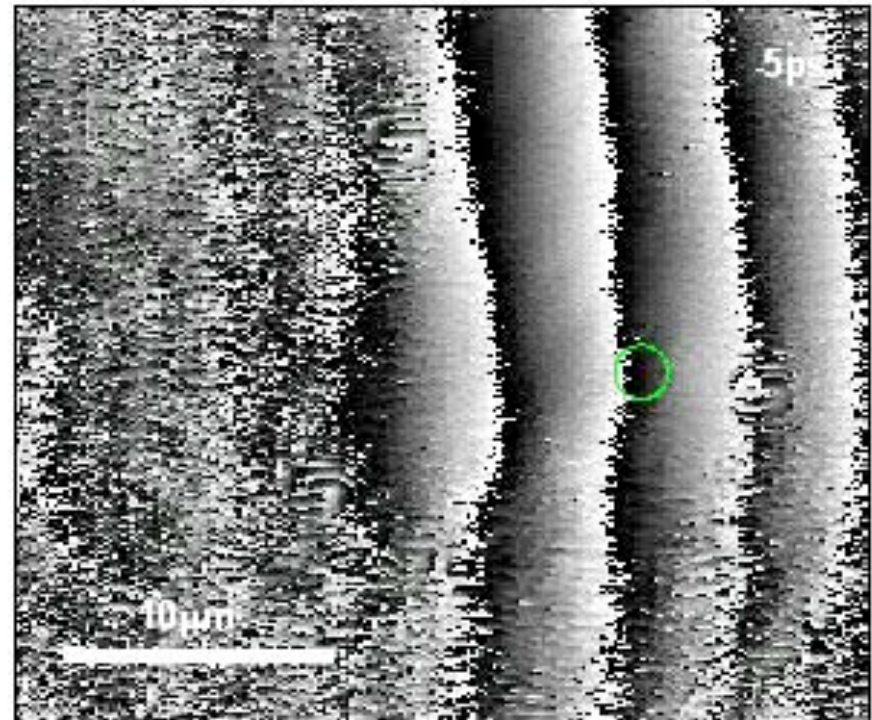
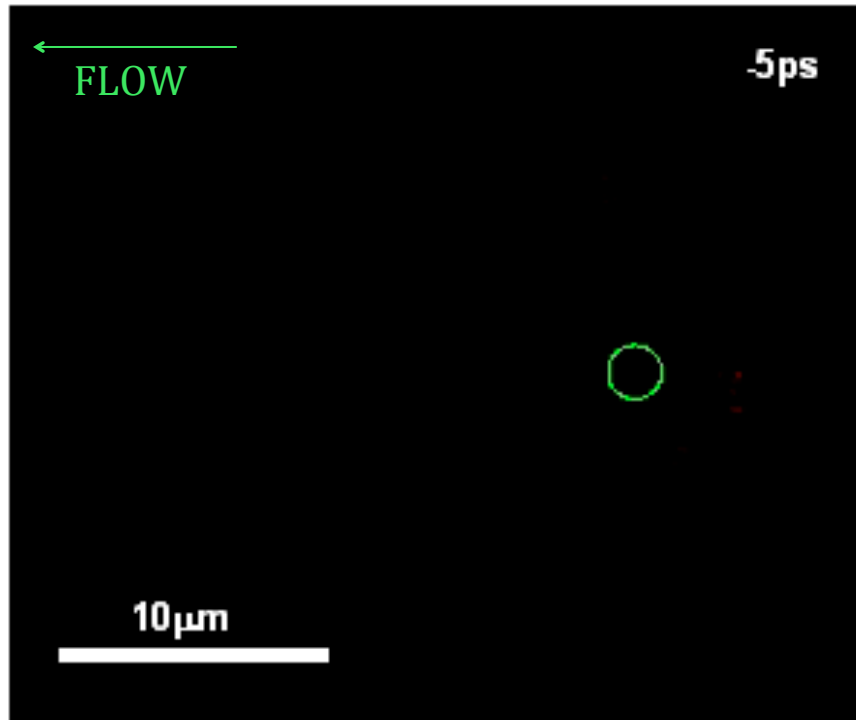
>?#\$\$%' 3\$-), 6+!\$)"#+@+ : / 3 / (*-\$+(\$)\$10/-

● A\$2/- , -)+B"62\$(+>?1'), 0/-C+3/3\$-)" 3+1/-)%/6

● D, 15EF\$5- (\$%++G-)\$%;\$%/ 3\$)\$%+@+B5, 2\$+, - (+03\$+'3, 9'-9



$H/\% \text{)} \$? + B, ' \% 2 + ' - +) 5 \$ + \mid , 8 \$ + / ; + , - + / J 2) , 16 \$$



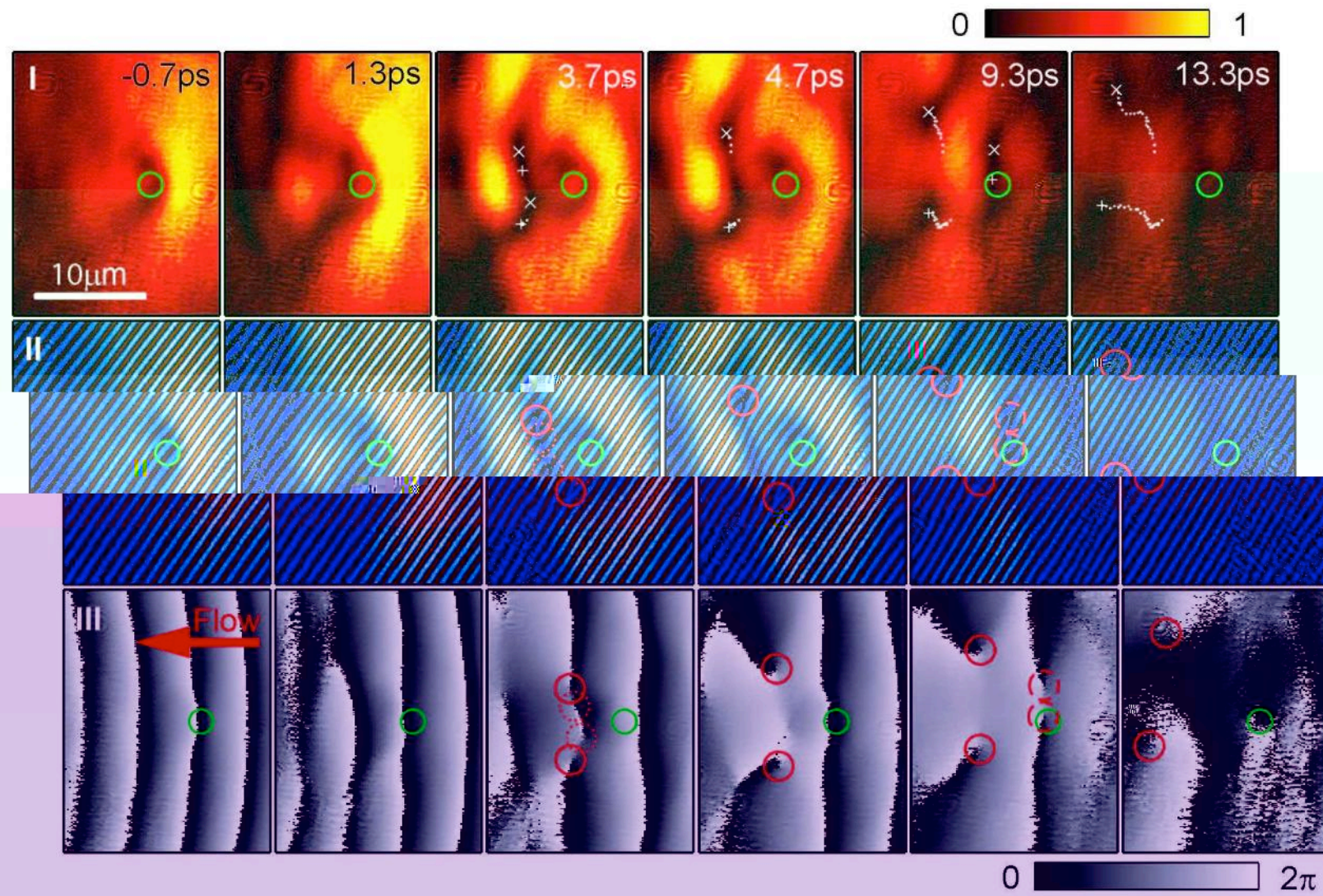
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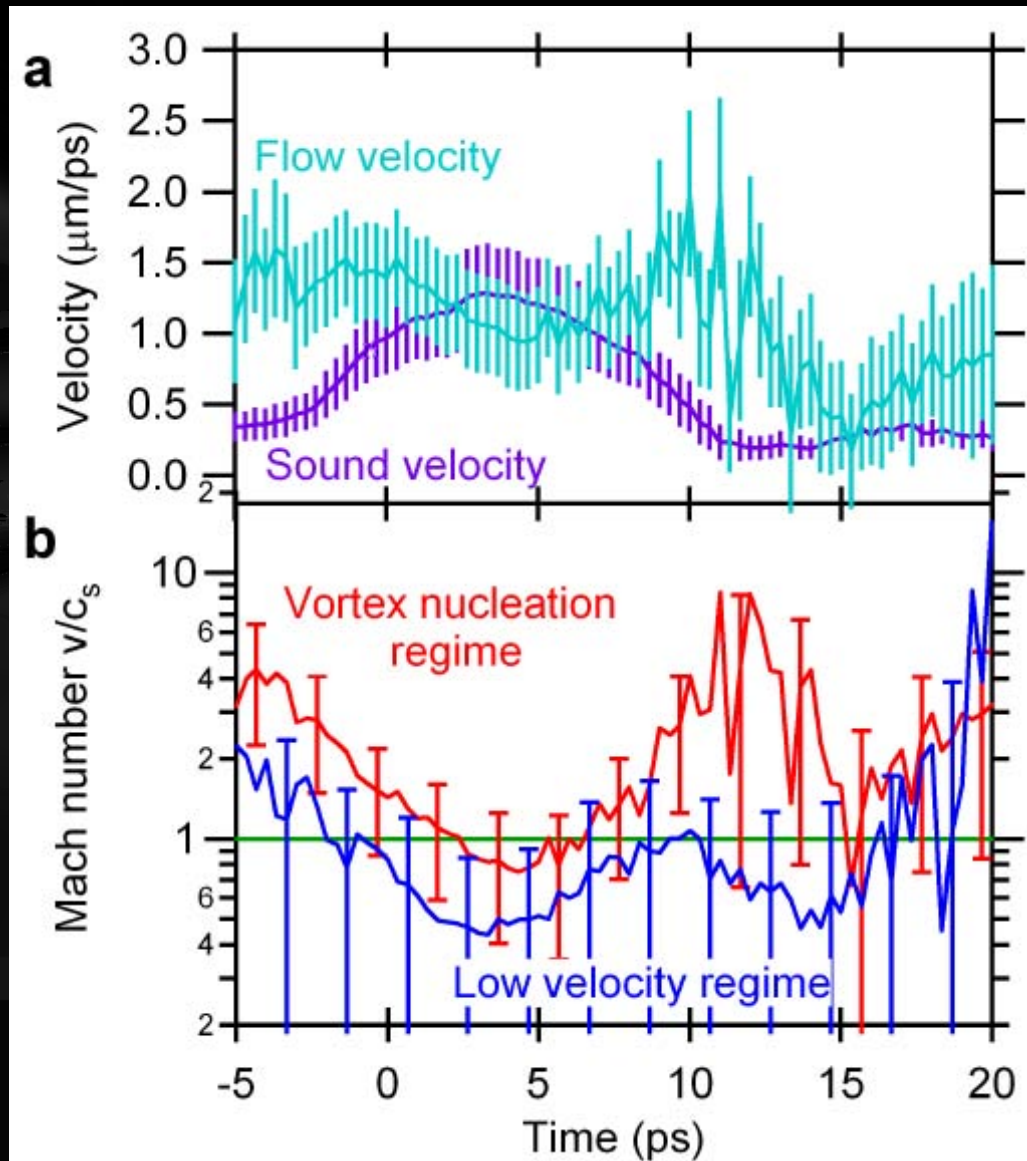
nature
physics

G. Nardin, G. Grosso *et al*, Nature Physics 7, 635–641 (2011)

H / %) \$? + - " 16 \$, 0 / - + % \$ 9 ' 3 \$



H/(%)\$?+B, '%2+K"16\$, 0/-+L/- ('0/-2

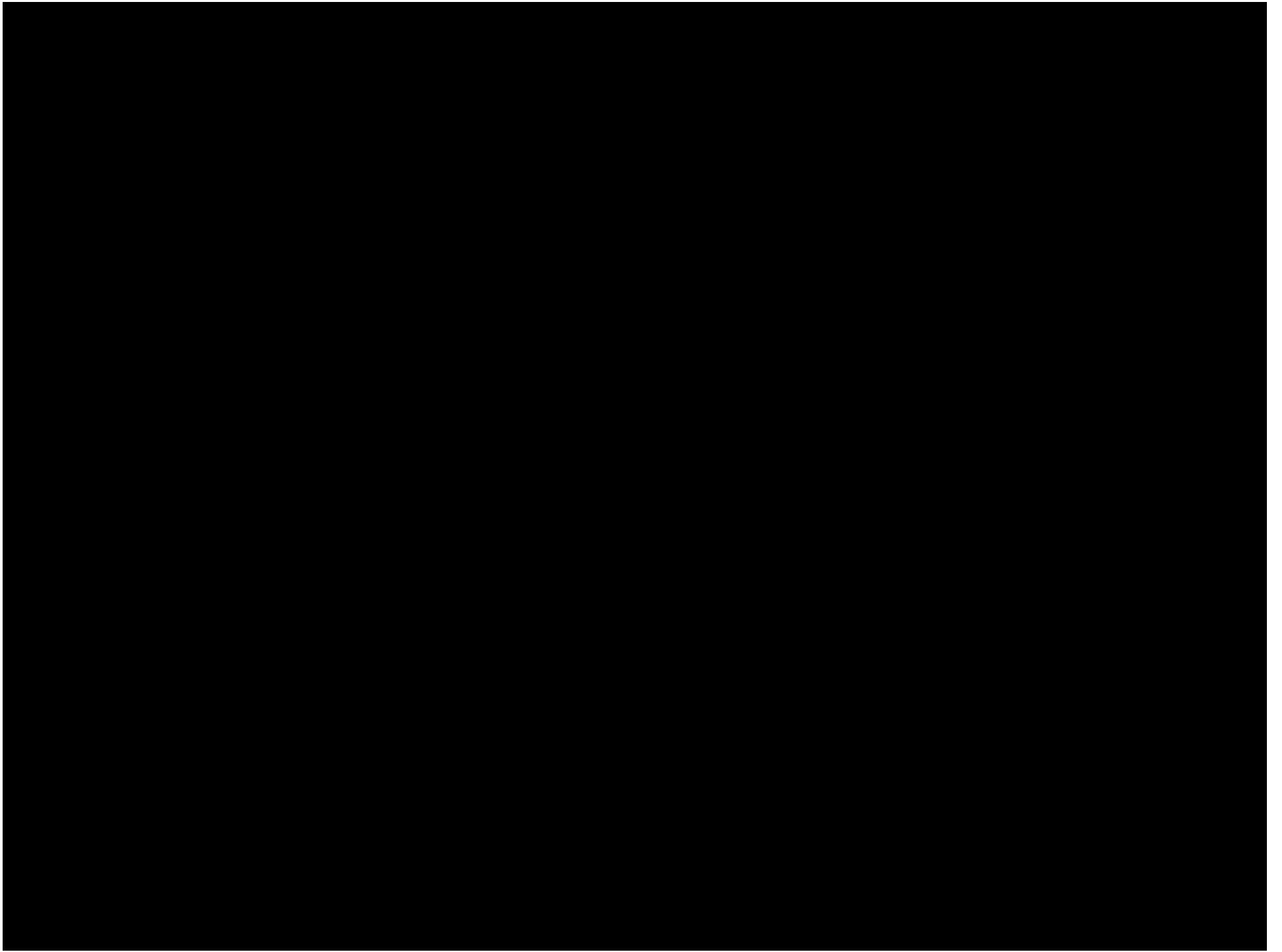


Experimental values of local v and c_s are estimated in the perimeter of the obstacle

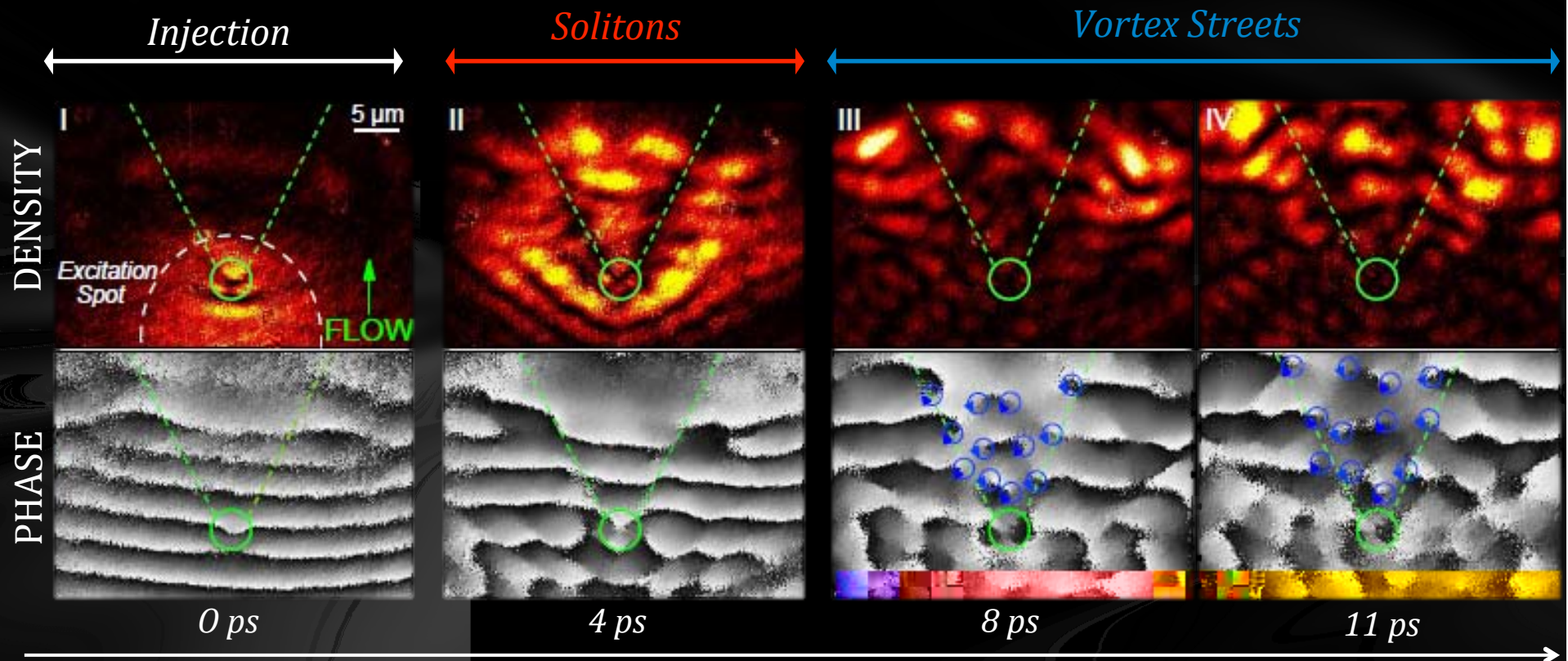
MACH NUMBER

$$v_{flow} = \frac{\hbar k_{\parallel}}{m}$$

$$\Rightarrow M = \frac{v_{flow}}{c_s}$$



$\langle '21/1', 0/-+/;+<, \%8+!/6')/-2+'-)/+./\%01\$2$



- B.&'&/%, '\$-5/)-"#\$%"3)0'"G#,)&#"31))%'&3-+, '-&#):\$', /5"3
- H\$: %.)/"3-%&3%):4'\$31)%.,) * . "#,)-"#\$%"3)#\$6,52,

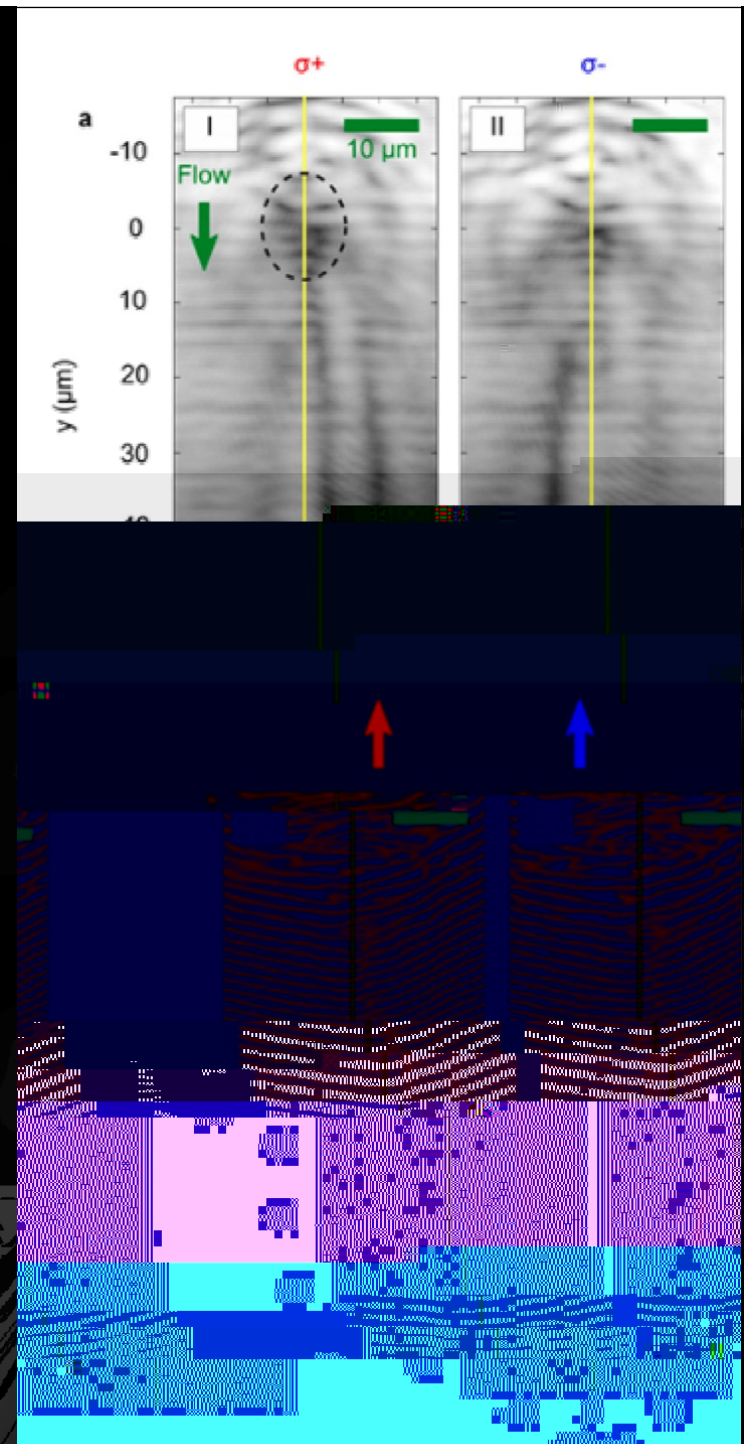
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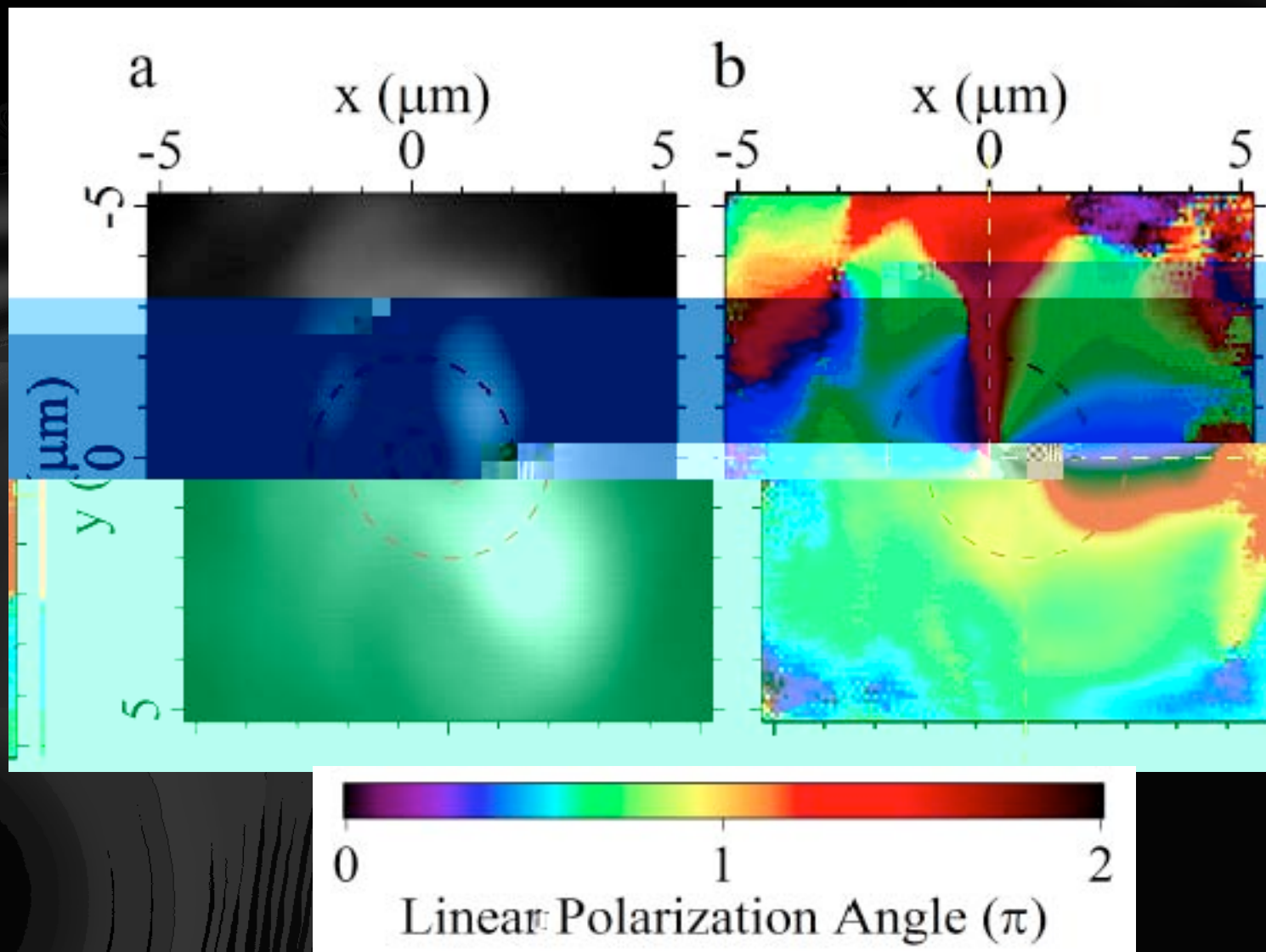
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The dream team



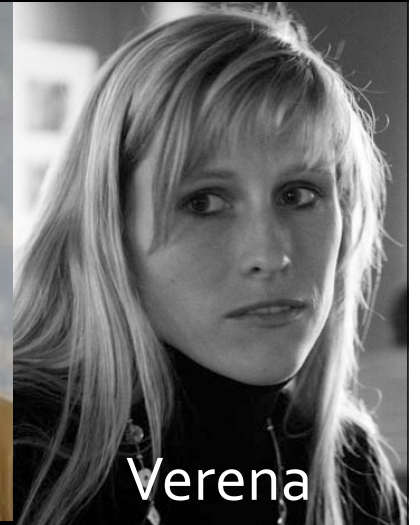
Konstantinos



Francesco



Gabriele



Verena



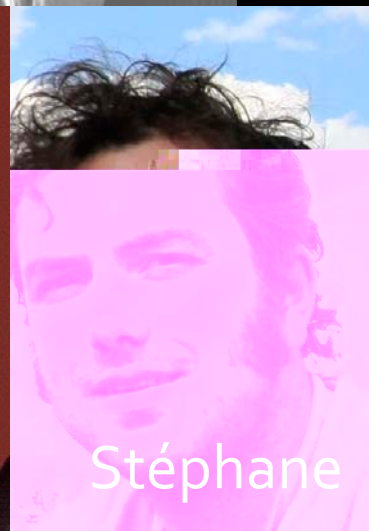
Marcia



Gael



Barbara



Stéphane



Hadis

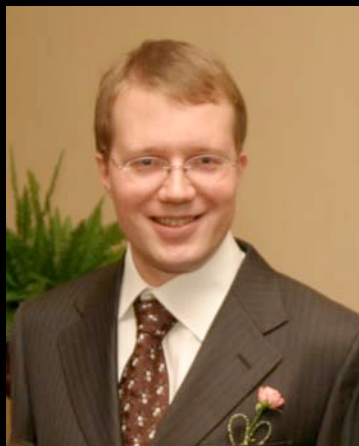
theorists



Vincenzo Savona
EPFL



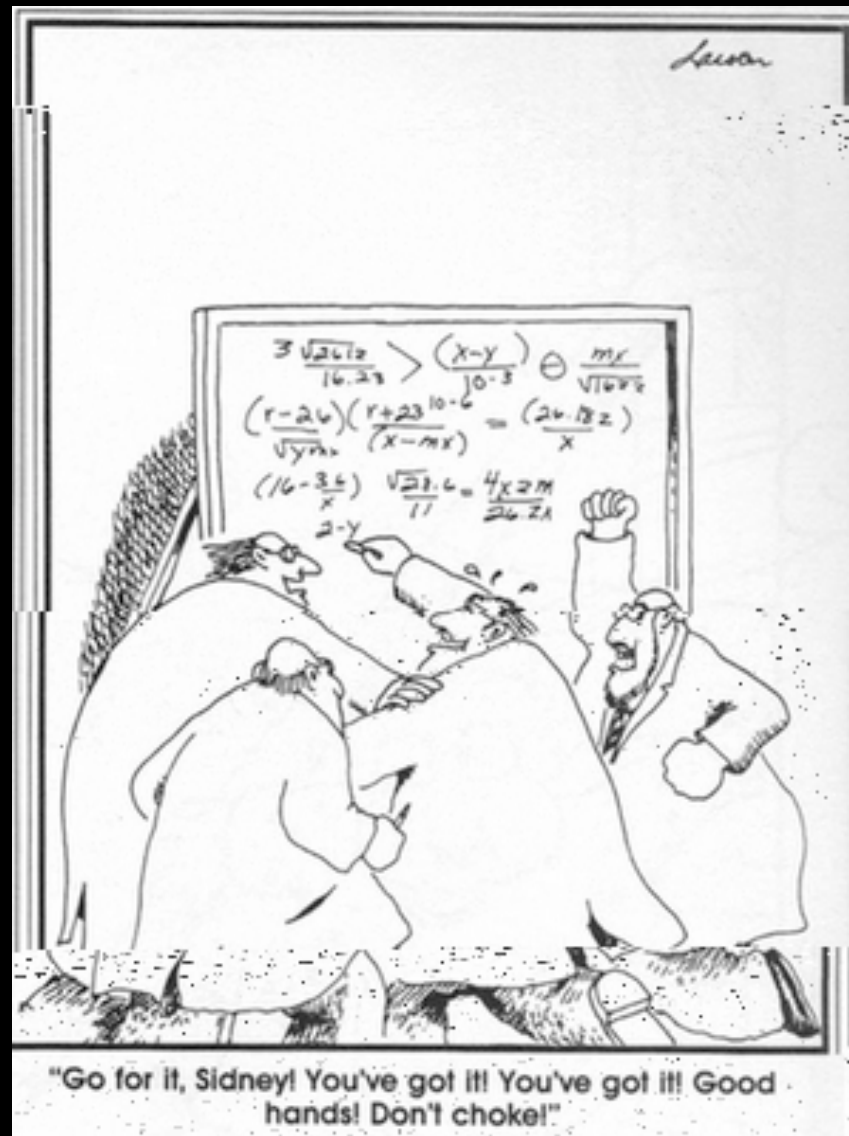
Michiel Wouters
Leuven



Alexei Kavokin
Southampton



Yuri Rubo
Mexico



"Knowledge is limited;
but imagination
encircles the world"

Lao Tzu

老子



An aerial photograph of a large body of water, likely a lake, with a city and mountains in the background. The image is overlaid with numerous horizontal lines in various colors (blue, pink, green, yellow, red, purple) that span the width of the frame. The text "Thank you / Merci" is centered in the upper half, and "谢谢" is centered below it.

Thank you / Merci

谢谢