Spinor hydrodynamics of polaritons in semiconductor microcavities

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LABORATOIRE
DE PHOTONIQUE
ET DE NANOSTRUCTURES

Kavli Institute for Theoretical Physics, Santa Barbara, October 2012

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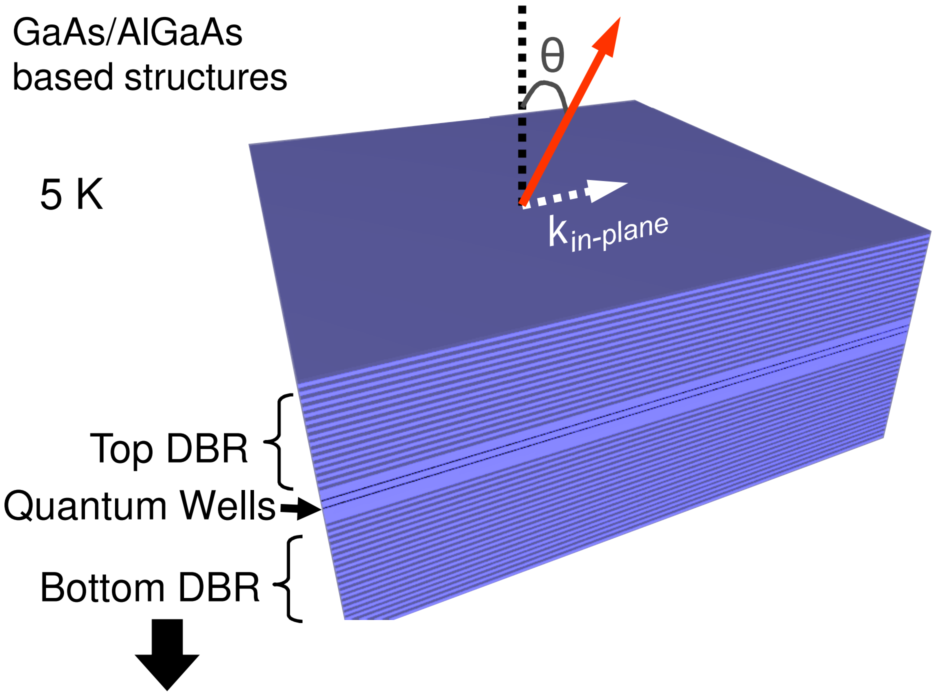
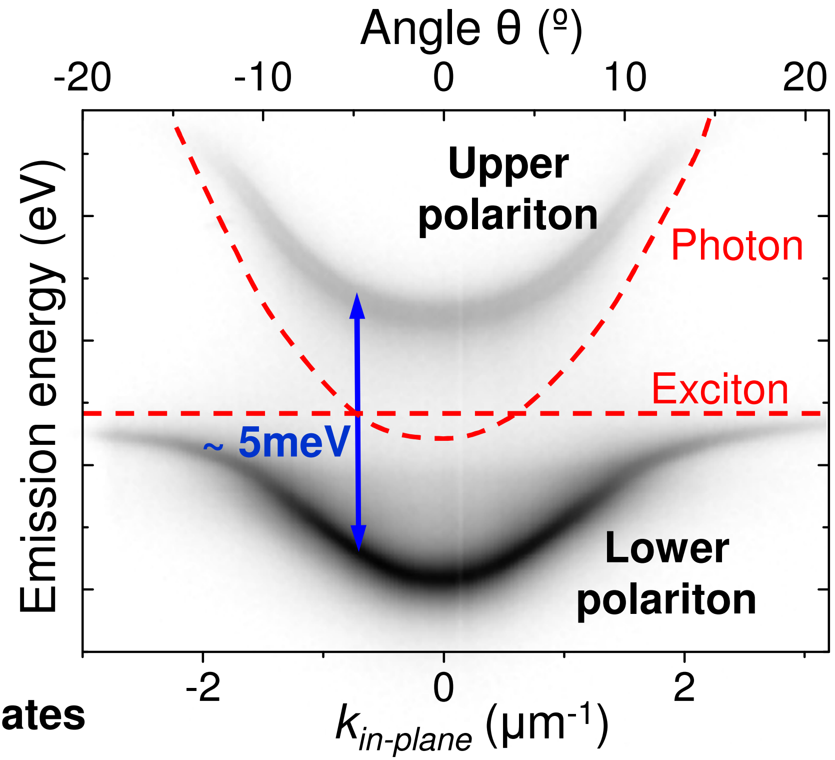
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Microcavity polaritons





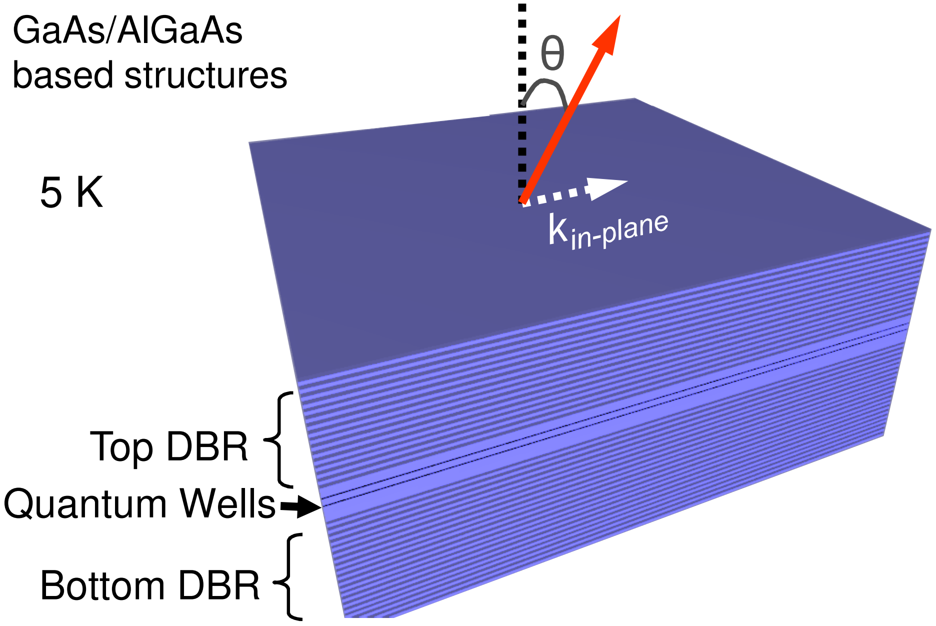
Microcavity polaritons : mixed exciton-photon states

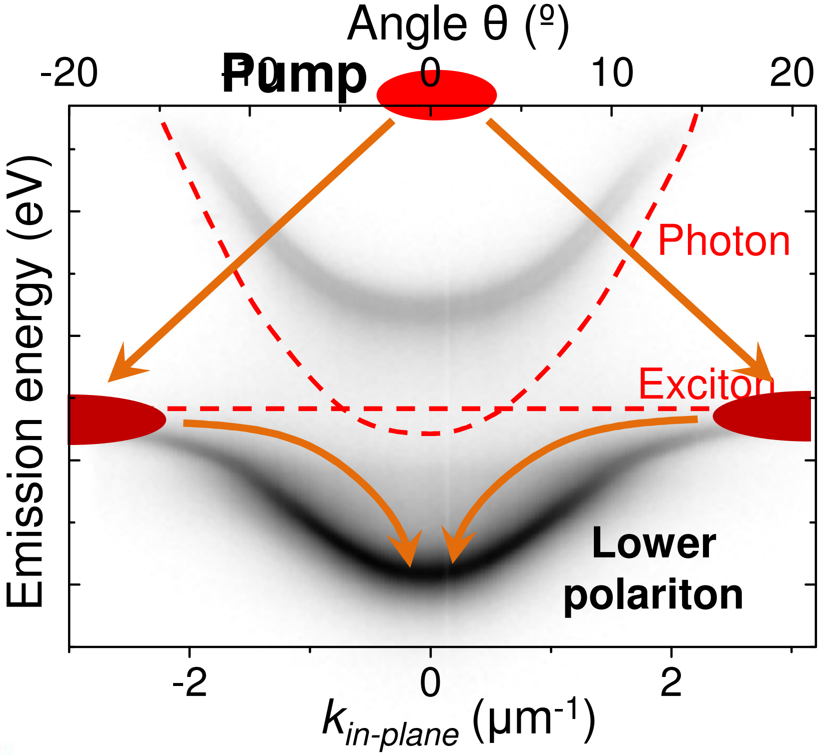
Properties

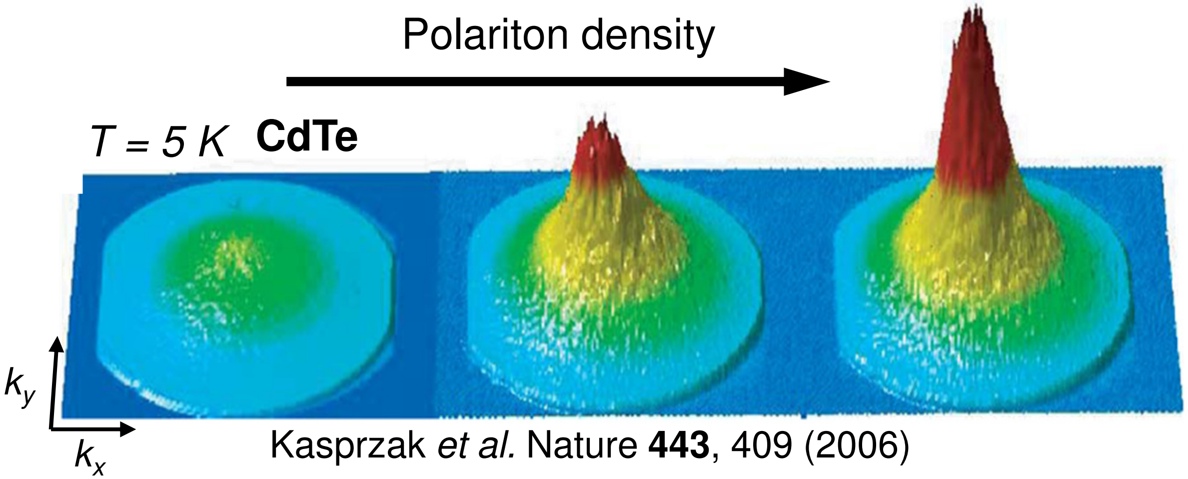
- Bosons
- Photonic component → **low mass (10^{-5} m_e)**
- Short lifetime (~1-50 ps) → **escape out of the cavity**
  Optical access to the polariton energy, momentum and space distrib.
- **Excitonic component → strong interactions**

Microcavity polaritons: condensation

GaAs/AlGaAs
based structures





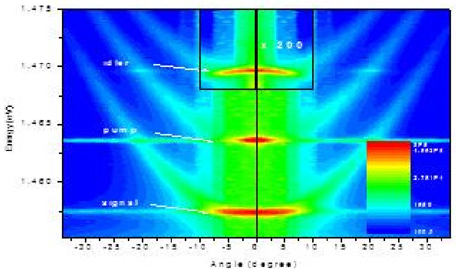


Kasprzak *et al.* Nature **443**, 409 (2006)

Balili *et al.*, Science **316**, 1007 (2007)

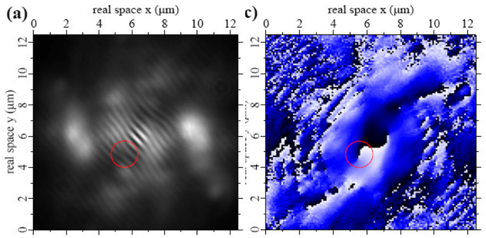
Polaritons: non-linear properties

Optical Parametric Oscillation



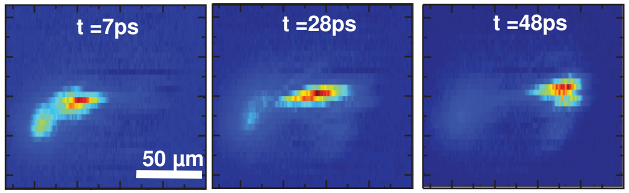
Diederichs *et al., Nature* **440**, 904 (2006)
Savvids *et al.*, PRL **84**, 1547 (2000)
Stevenson *et al.*, PRL **85**, 3680 (2000)

Quantised vortices

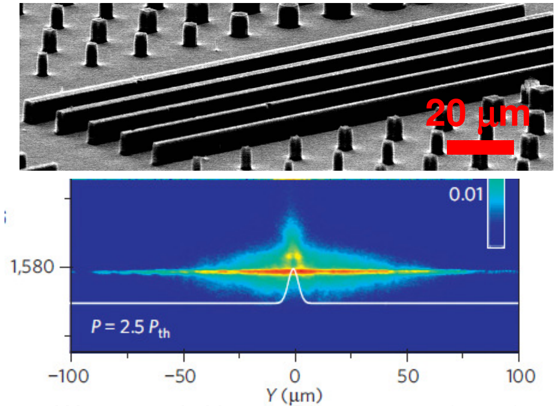


Lagoudakis *et al.*, Nature Phys. **4**, 706 (2008), and Science **326**, 974 (2009)
Sanvitto *et al.*, Nature Phys. **6**, 527 (2010)
Krizhanovskii *et al.*, PRL **104**, 126402 (2010)
Roumpos *et al.*, Nature Phys. **7**, 129 (2010)

Coherent propagation

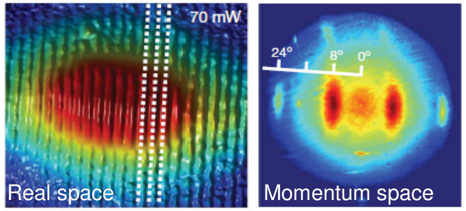


AA, Sanvitto *et al.,* Nature **457**, 295 (2009)



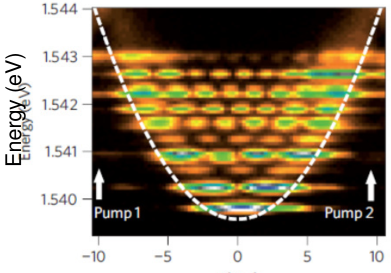
Wertz *et al.*, Nature Phys. **6**, 860 (2010)
Tanese *et al.*, PRL **108**, 036045 (2012)

Long-range order phases



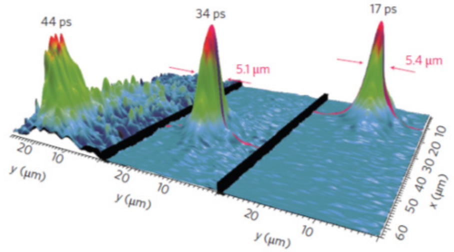
Lai *et al.,* Nature **450**, 529 (2007)
Kim et al. Nature Phys. (2011)

Harmonic oscillators



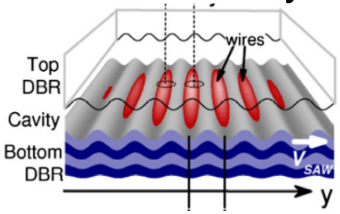
Tosi *et al.*, Nature Phys. **8**, 190 (2012)

Bright solitons



Sich *et al.*, Nature Phot. **6**, 50 (2012)

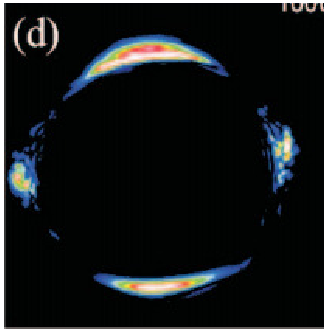
1D BEC arrays



Cerda-Méndez *et al.,* PRL 105, 116402 (2010)

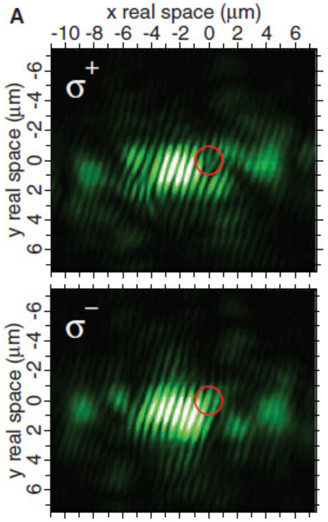
Polariton spin phenomena

Spin-dependent parametric oscillation



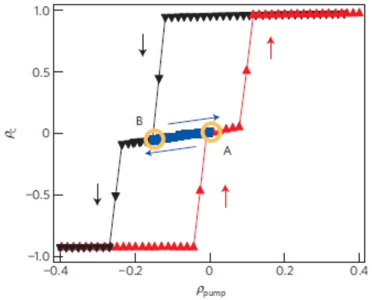
Lagoudakis *et al.,* PRB **65**, 161310 (2002)
Shelykh *et al.*, PRB **70**, 035320 (2004)
Krizhanovskii *et al.*, PRB **73**, 073303 (2006)
Romanelli *et al.*, PRL **98**, 106401 (2007)

Half-vortices



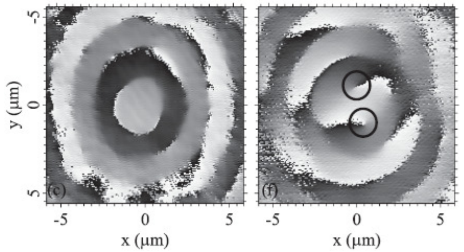
Lagoudakis *et al.,* Science **326**, 974 (2009)
Rubo, PRL **99**, 106401 (2007)

Polarisation multi-stability



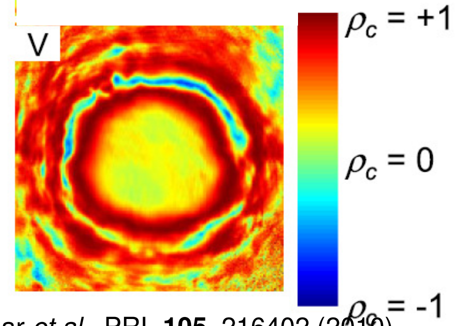
Paraïso *et al.,* Nature Mat. **9**, 655 (2010)
Gippius *et al.*, PRL **98**, 236401 (2007)

Polarisation conversion



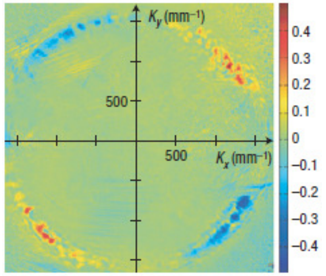
Manni *et al.,* PRB. **83**, 241307 (2011)

Spin rings



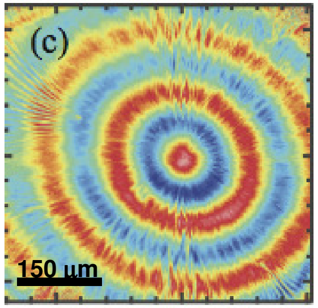
Sarkar *et al.*, PRL **105**, 216402 (2010)
Adrados *et al.*, PRL **105**, 216403 (2010)
Shelykh *et al.*, PRL **100**, 116401 (2008)

Optical Spin Hall Effect



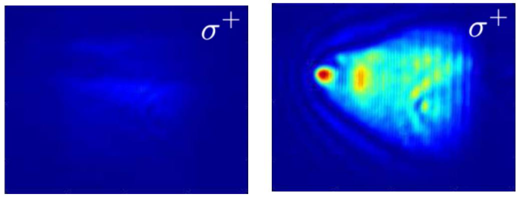
Leyder *et al.,* Nature Phys. **3**, 628 (2007)
AA, Liew *et al.*, PRB **80**, 165325 (2009)
Maragkou *et al.,* Optics Lett. **36**, 1095 (2011)
Kavokin *et al.*, PRL **95**, 136601 (2005)

Spin precession



Kammann *al.*, PRL **109**, 036404 (2012)

Spin-switches



AA, Liew *et al.*, Nature Phot. **4**, 361 (2010)

Adrados *et al.*, PRL **107**, 146402 (2011)

Outline

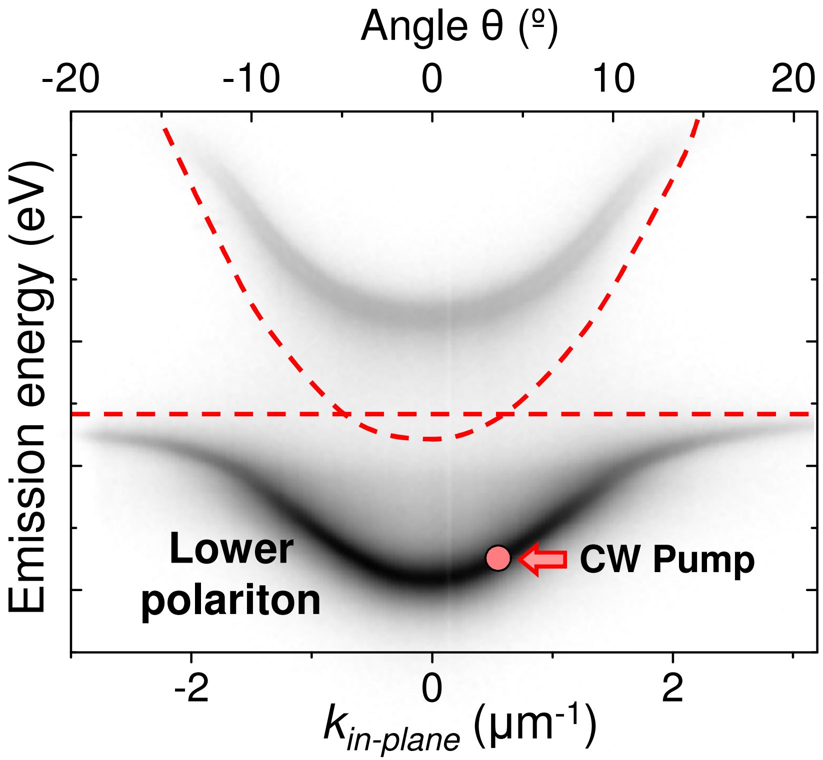
⇨ **Scalar hydrodynamics of polariton condensates**

- Dark solitons
- Vortex streets

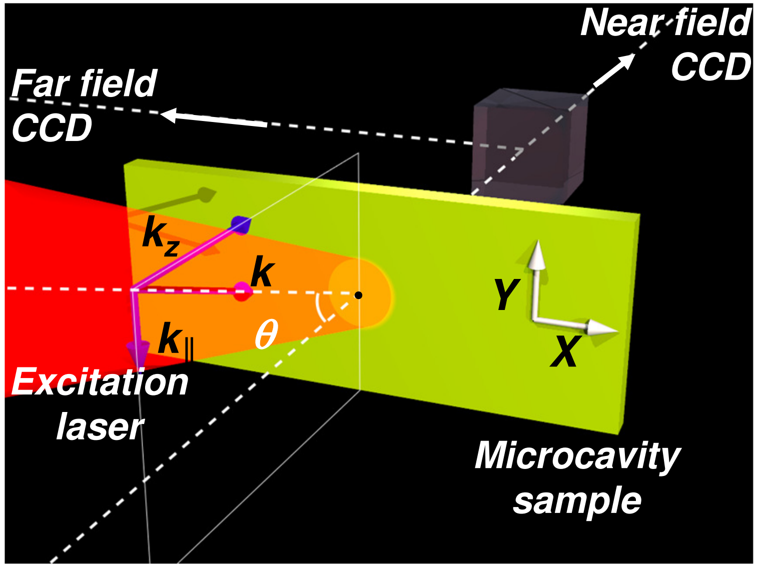
⇨ **Spinor hydrodynamics**

- Spin-helix propagation
- Half-solitons: magnetic monopoles

Resonantly driven polariton gas



Transmission experiment in a InGaAs/GaAs/AlAs microcavity



T=10 K

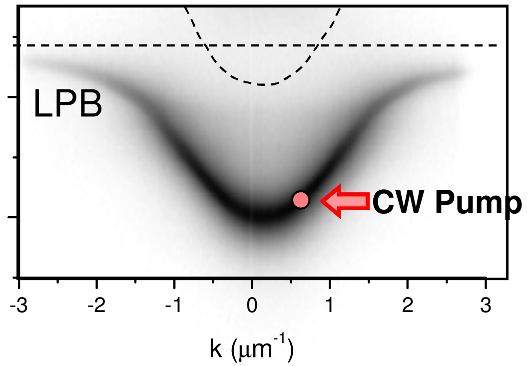
- Controlled energy (~chemical potential)
- Controlled momentum (excitation angle)
- Controlled density
- **Steady state: interplay between pumping and decay**

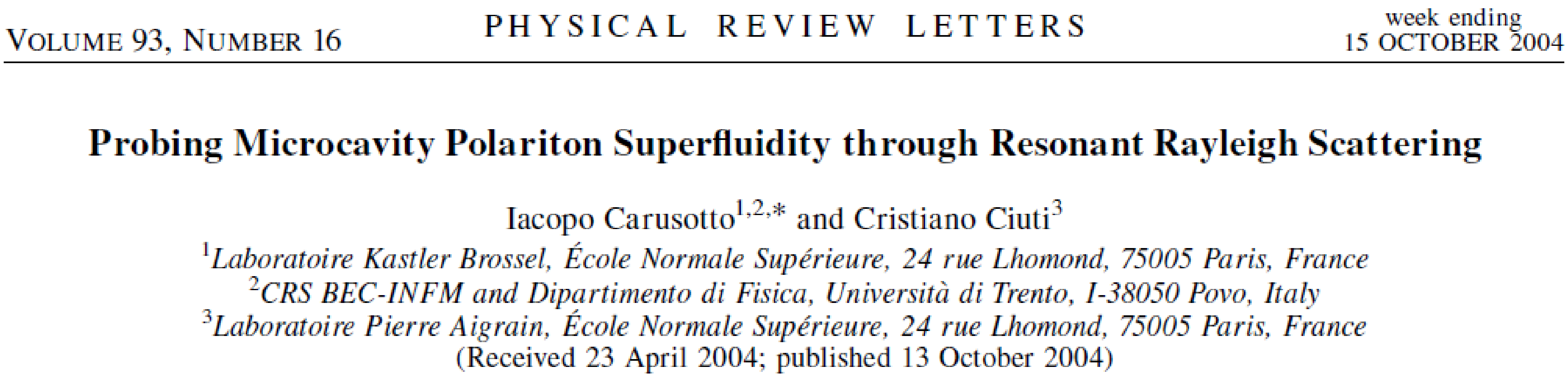
Polariton interactions: superfluidity

Non-linear Schrödinger equation

$$i\partial_t\psi(x,t)=\left[\underset{\substack{\swarrow\\\text{normal mode}\\\text{coupling}}}{D}-i\underset{\substack{\downarrow\\\text{decay}}}{\gamma/2}+\underset{\substack{\downarrow\\\text{potential}}}{V\left(x\right)}+g\underset{\substack{\searrow\\\text{pol-pol}\\\text{interaction}}}{\left|\psi(x,t)\right|^2}\right]\psi(x,t)+\underbrace{F_Pe^{i(k_Px-\omega_Pt)}}_{\text{CW Pump}}$$

Resonant excitation




VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Probing Microcavity Polariton Superfluidity through Resonant Rayleigh Scattering

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[3]*Laboratoire Pierre Aigrain, École Normale Supérieure, 24 rue Lhomond, 75005 Paris, France*
(Received 23 April 2004; published 13 October 2004)

See also: Bolda, et al., PRL **86**, 416 (2001),
Chiao, et al., PRA **60**, 4114 (1999)

Polariton interactions: superfluidity

Non-linear Schrödinger equation

$$i\partial_t\psi(x,t)=\left[D-i\gamma/2+V(x)+g\left|\psi(x,t)\right|^2\right]\psi(x,t)+\underbrace{F_P e^{i(k_P x-\omega_P t)}}_{\text{CW Pump}}$$

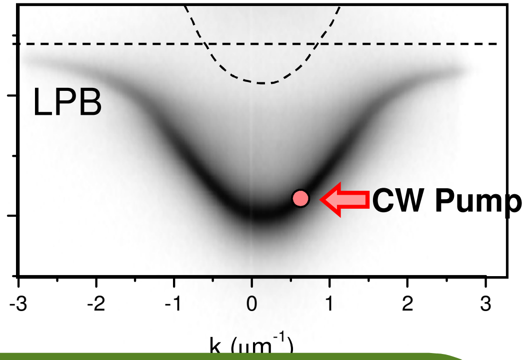
normal mode coupling

decay

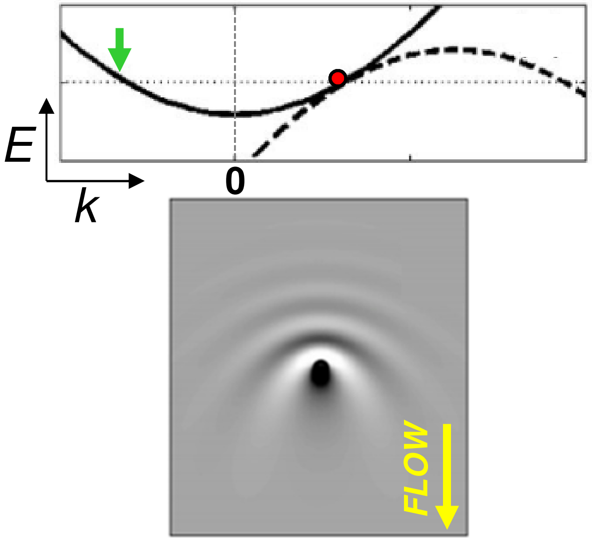
potential

pol-pol interaction

Resonant excitation

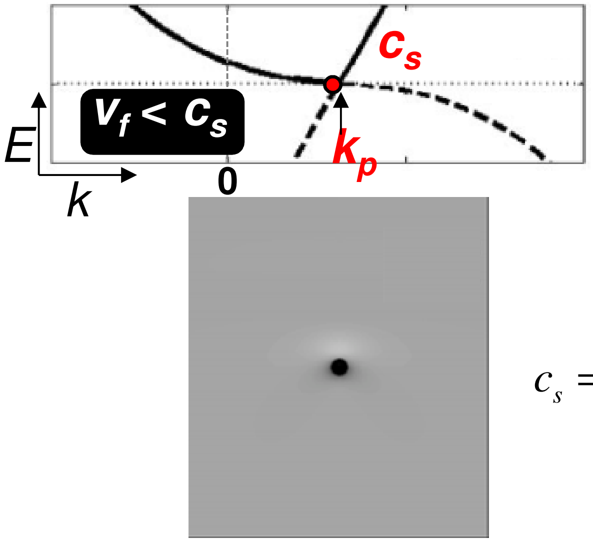


Low power



Elastic scattering

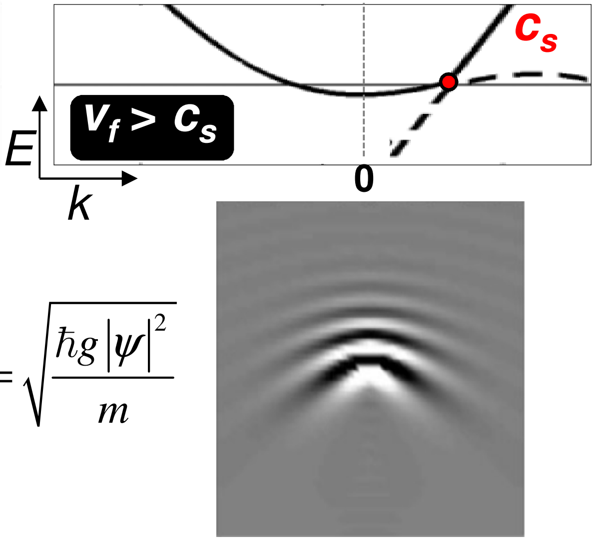
High power
low momentum



Superfluid

$$c_s=\sqrt{\frac{\hbar g|\psi|^2}{m}}$$

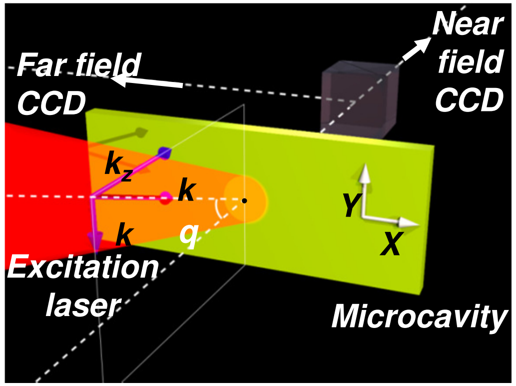
High power
high momentum



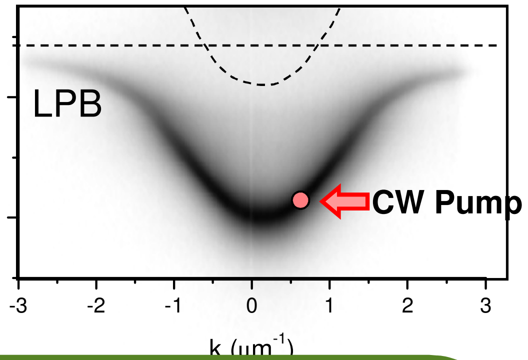
Supersonic

Carusotto and Ciuti, PRL **93,** 166401 (2004)

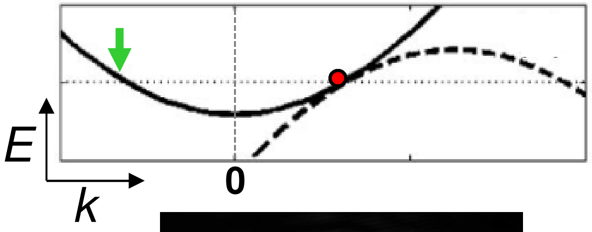
Polariton interactions: superfluidity

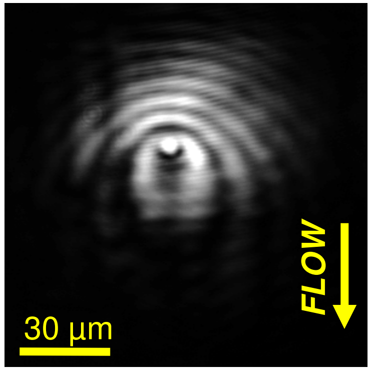


Resonant excitation



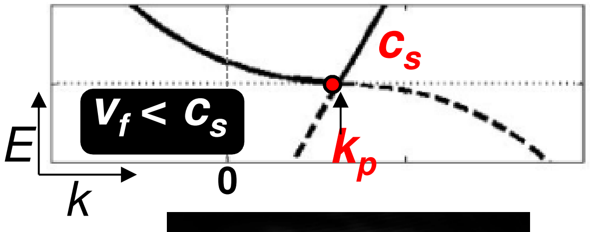
Low power

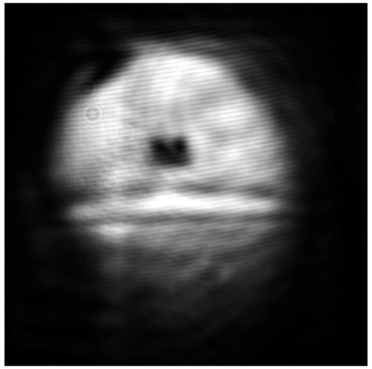




Elastic scattering

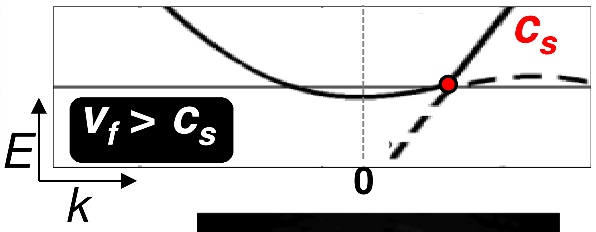
High power
low momentum



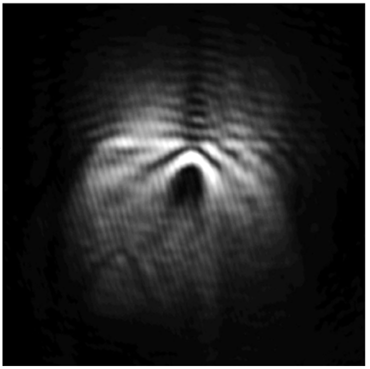


Superfluid

High power
high momentum



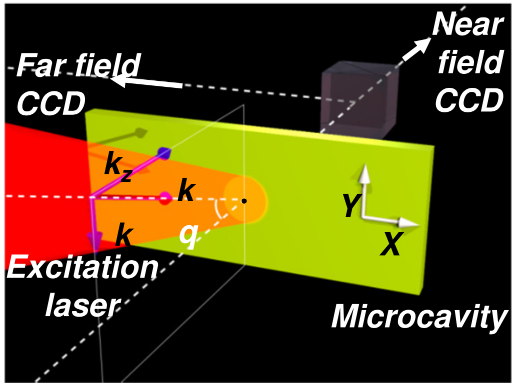
$$c_s = \sqrt{\frac{\hbar g|\psi|^2}{m}}$$



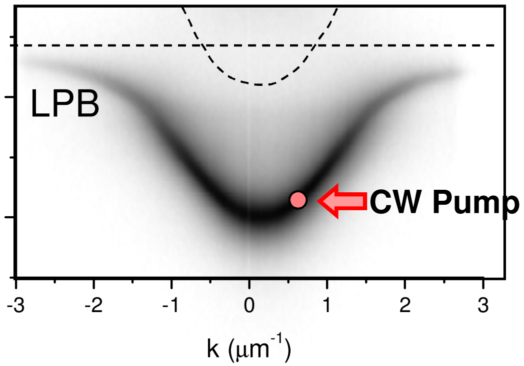
Supersonic

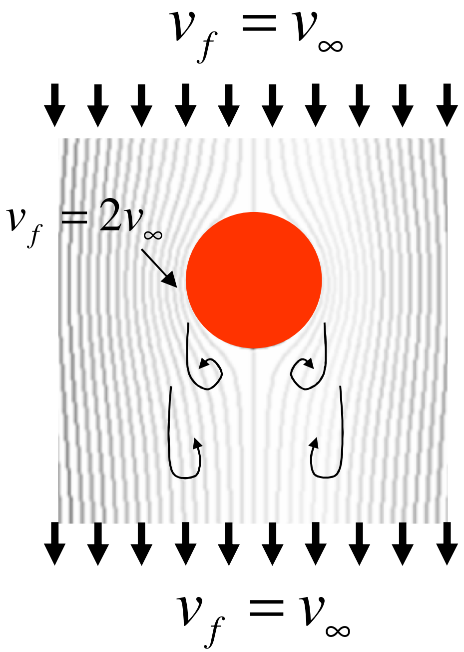
Nature Physics **5**, 805 (2009)

Beyond superfluidity: hydrodynamic excitations



Resonant excitation





- Inhomogeneous velocity around obstacle

$$v_f(\boldsymbol{r},t) = \frac{\hbar}{m}\nabla\phi(\boldsymbol{r},t)$$

- Nucleation of topological excitations

  even at $v_\infty < c_s$

Pigeon *et al.*, PRB 83, 144513 (2011)

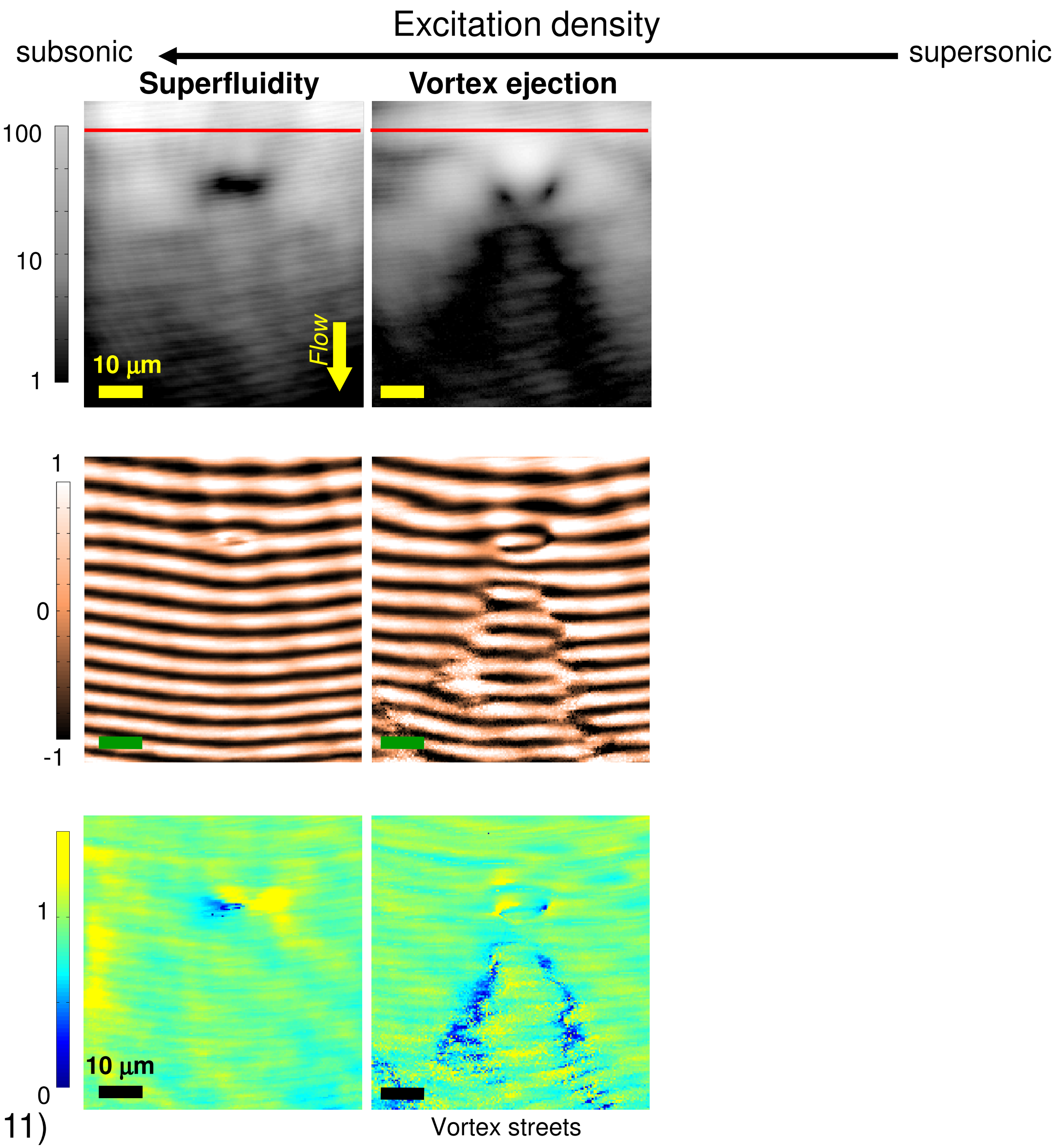
Soliton and vortex streets

v_f = 0.79 µm/ps
k=0.34 µm^{-1}

Real space emission

Interference with a coherent reference beam

Visibility of fringes (degree of coherence at τ=0)

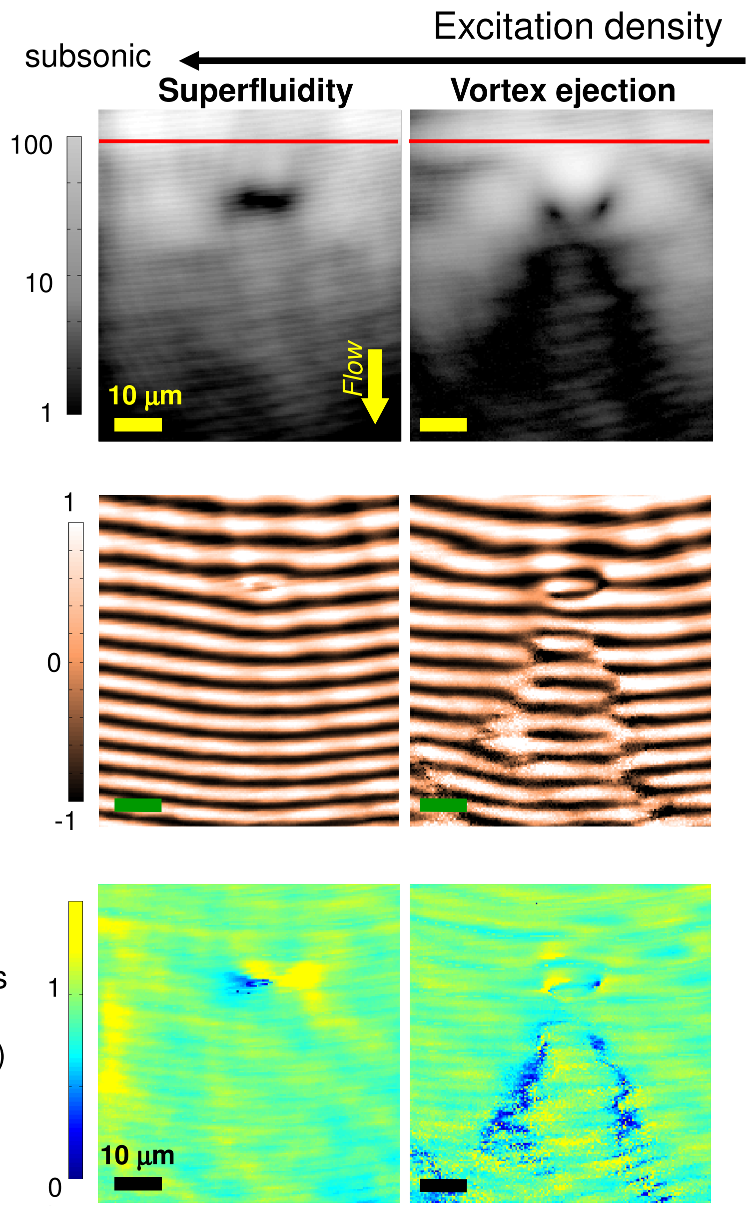


$$c_s = \sqrt{\frac{\hbar g \left|\psi\right|^2}{m}}$$

Science **332**, 1167 (2011)

Soliton and vortex streets

$v_f = 0.79$ μm/ps
$k = 0.34$ μm^{-1}



Real space emission

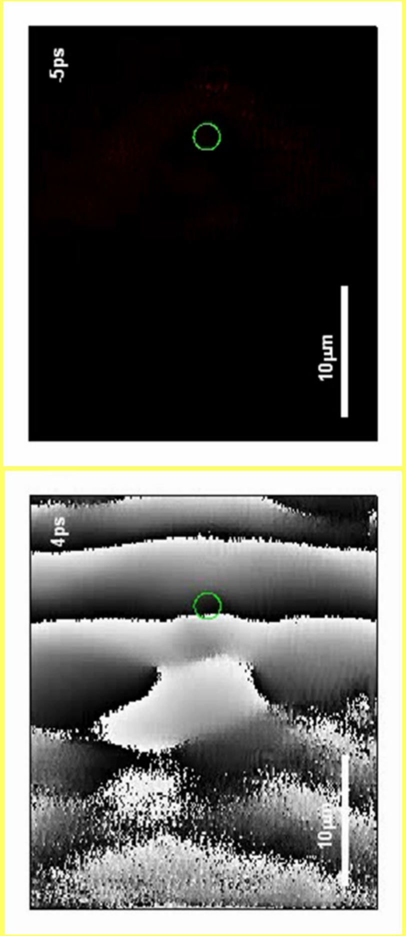
Interference with a coherent reference beam

Visibility of fringes (degree of coherence at τ=0)

Science **332**, 1167 (2011)

Vortex streets

Time resolved



Deveaud's group (EPFL)
Nardin *et al.*,Nature Phys. **7**, 635 (2011)

See also:
Sanvitto *et al.*, Nature Phot. **5**, 610 (2011)

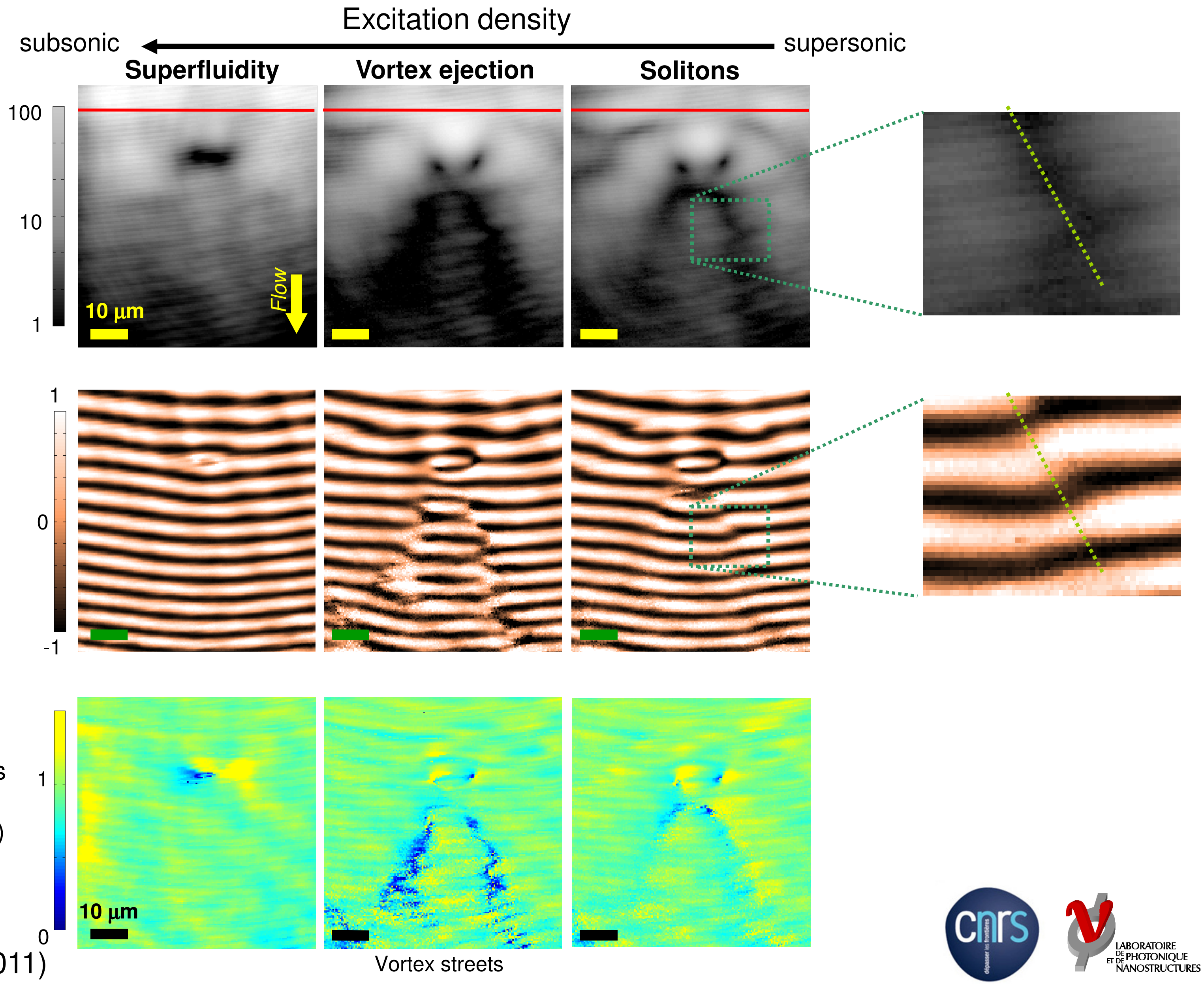
Soliton and vortex streets

$v_f = 0.79\ \mu\text{m/ps}$
$k = 0.34\ \mu\text{m}^{-1}$

Real space emission

Interference with a coherent reference beam

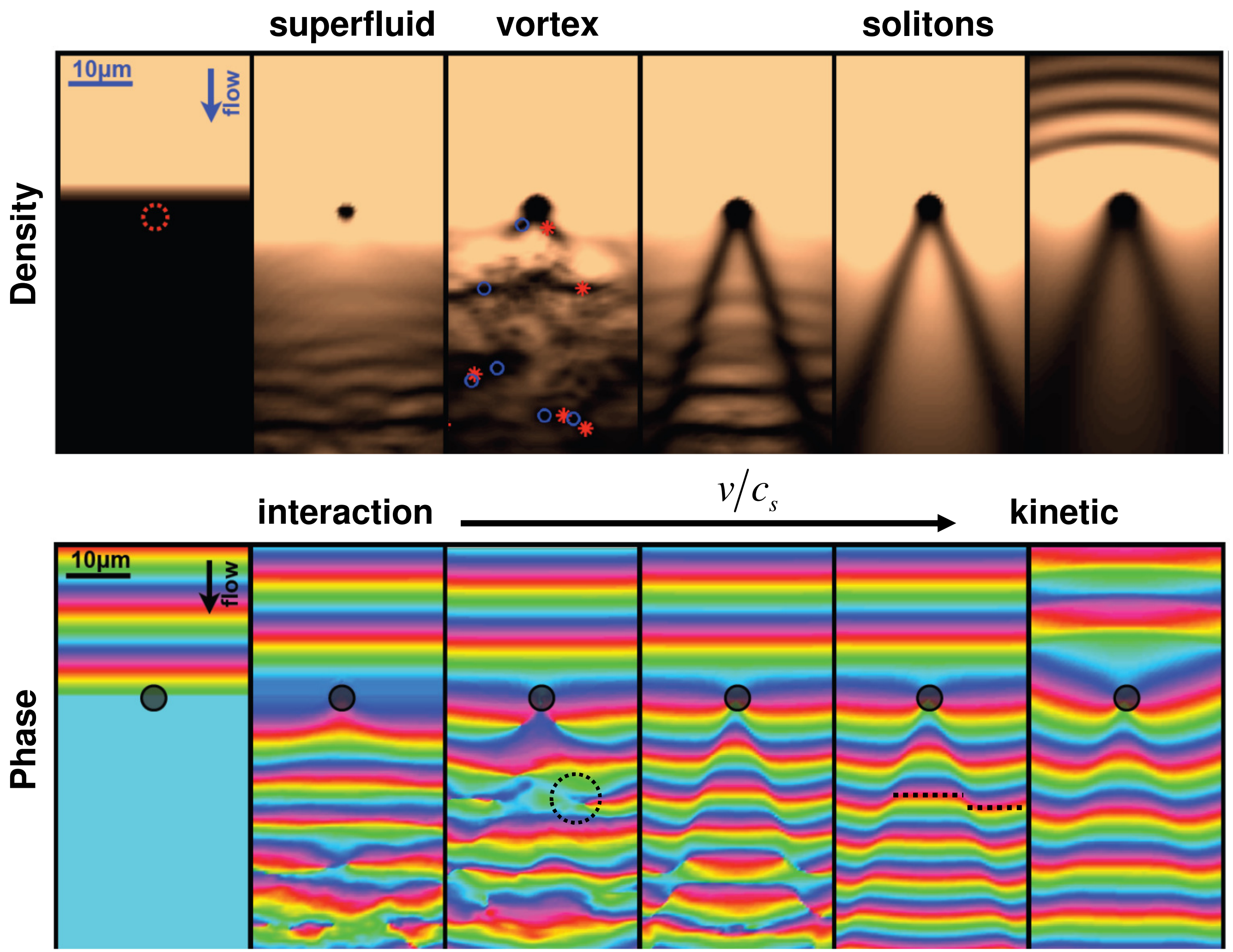
Visibility of fringes (degree of coherence at $\tau = 0$)



Science **332**, 1167 (2011)

GPE simulations

$$i\partial_t\psi(x,t)=\left[D-i\gamma/2+V\left(x\right)+g\left|\psi(x,t)\right|^2\right]\psi(x,t)+F_P\left(x\right)e^{i(k_Px-\omega_Pt)}$$



Pigeon *et al.*, PRB **83**, 144513 (2011)

Non-equilibrium Gross-Pitaevskii equation

⇩

Transition from superfluid to vortex emission and soliton nucleation

Topological excitations

Vortices ⇨ phase dislocation

Solitons ⇨ phase slip

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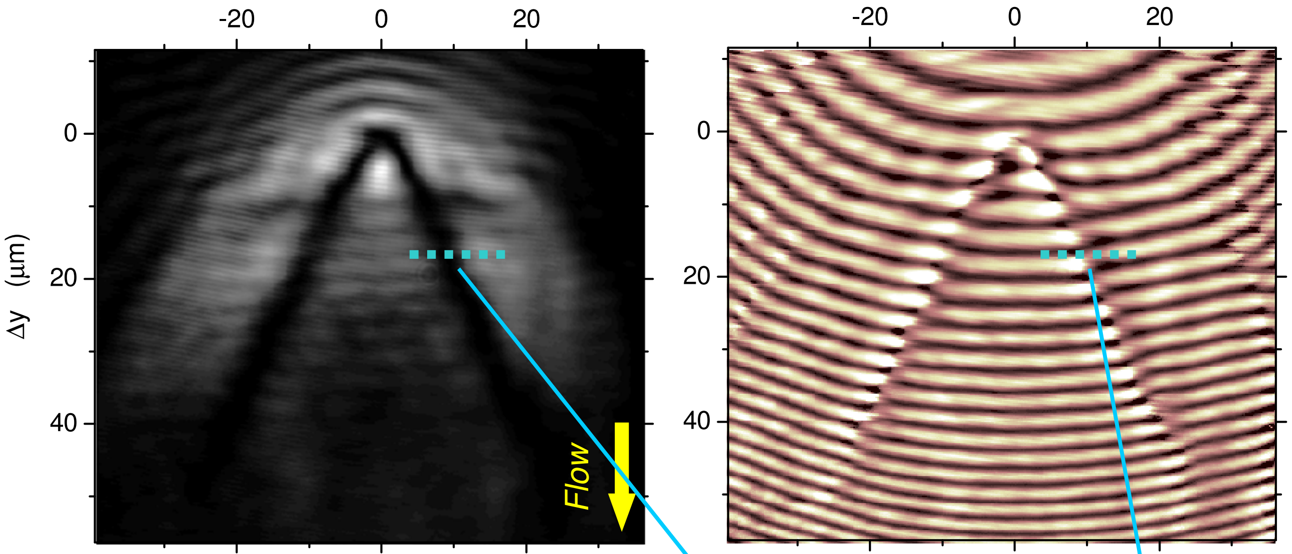
Soliton nucleation

$v_f = 1.7\ \mu\text{m/ps}$
$k = 0.73\ \mu\text{m}^{-1}$

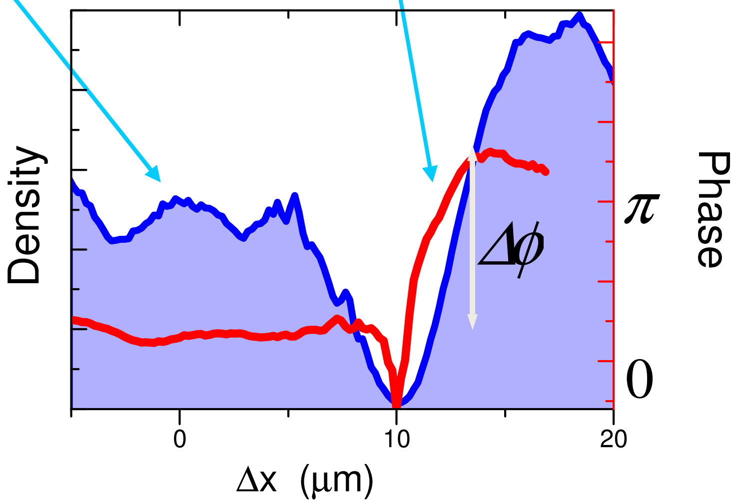
High speed



- 1D soliton in the *x*-direction
  y-direction: time coordinate
  movement of the soliton

El *et al.*, PRL **97**, 180405 (2006)

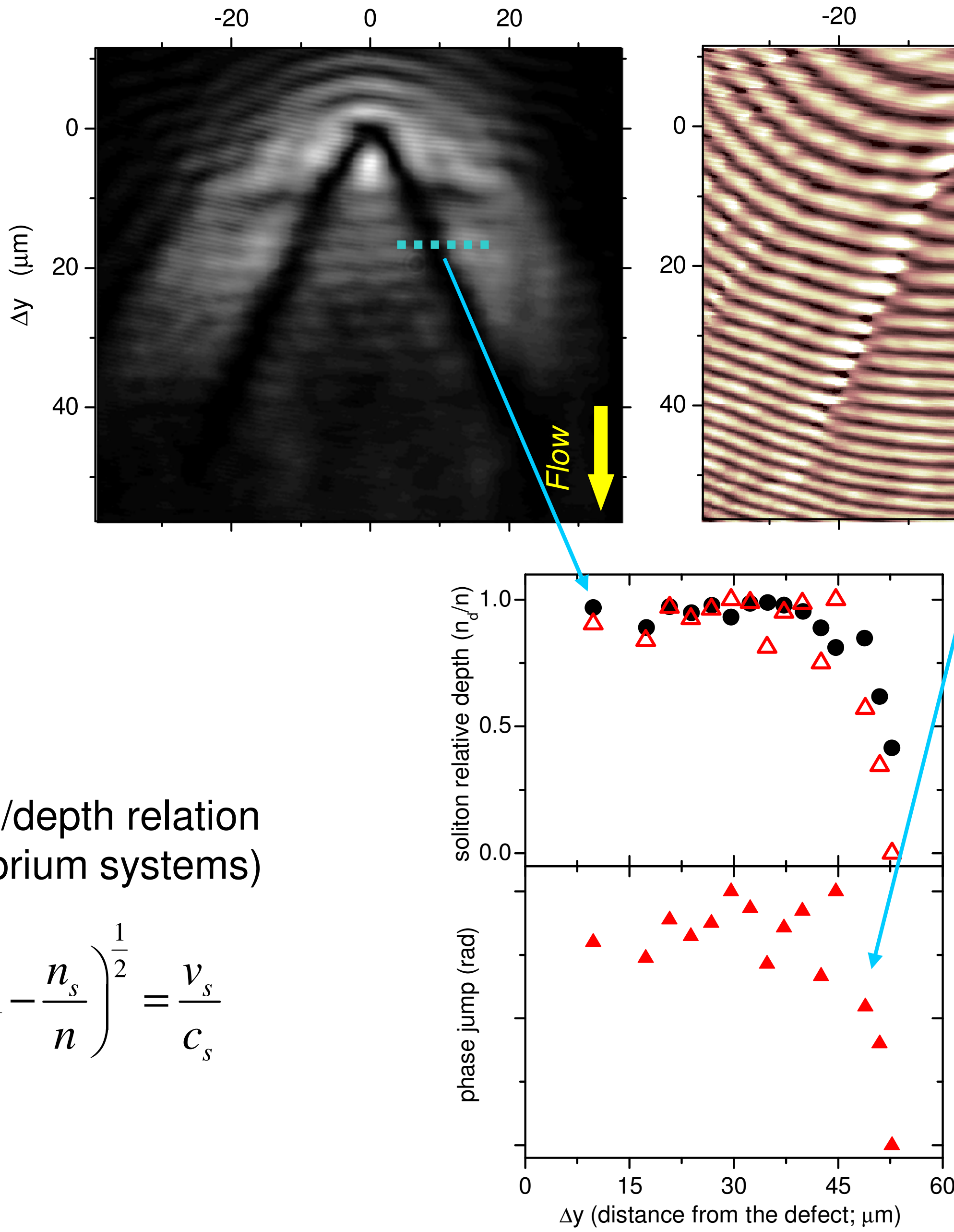
$$\psi\left(x - vt\right) = \sqrt{n}\left[i\frac{v}{c} + \sqrt{1 - \frac{v^2}{c^2}}\tanh\left(\frac{x - vt}{\xi\sqrt{2}}\sqrt{1 - \frac{v^2}{c^2}}\right)\right]$$



Characteristic phase jump

Science **332**, 1167 (2011)

Soliton nucleation



Phase jump/depth relation
(from equilibrium systems)

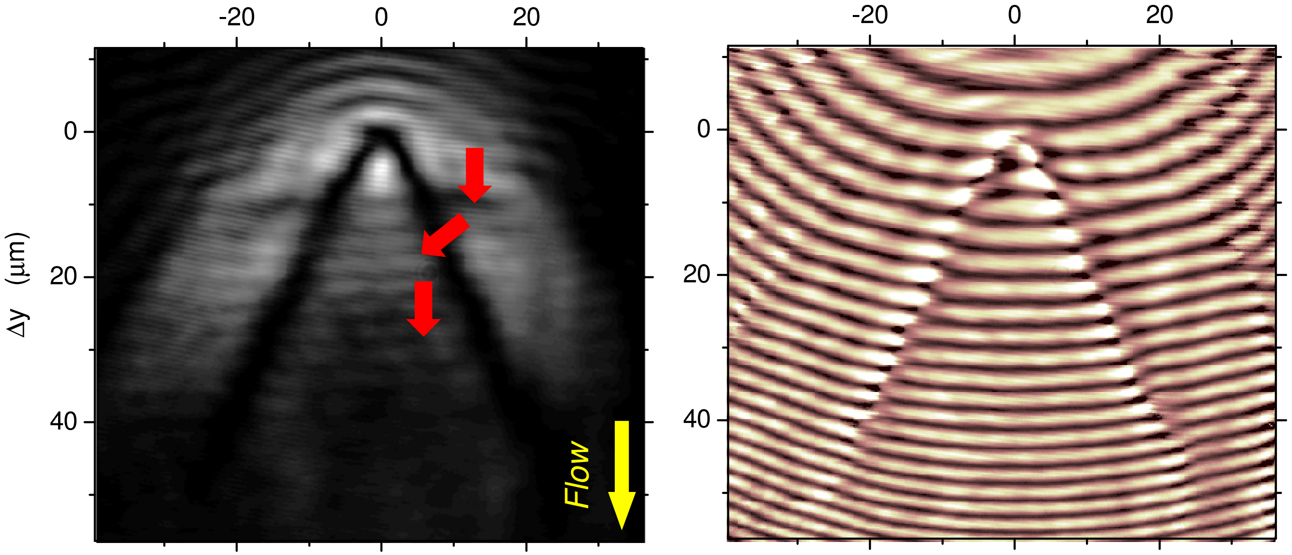
$$\cos\frac{\phi}{2} = \left(1 - \frac{n_s}{n}\right)^{\frac{1}{2}} = \frac{v_s}{c_s}$$

Soliton nucleation

$v_f = 1.7\ \mu m/ps$
$k = 0.73\ \mu m^{-1}$

⇩

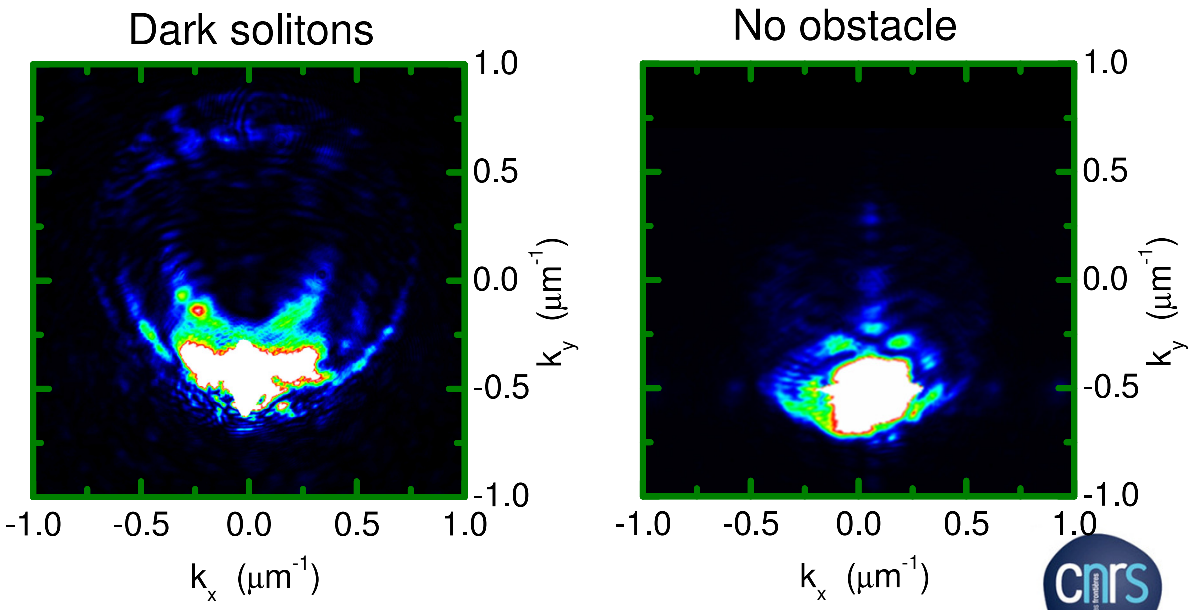
High speed



Momentum space

⇩

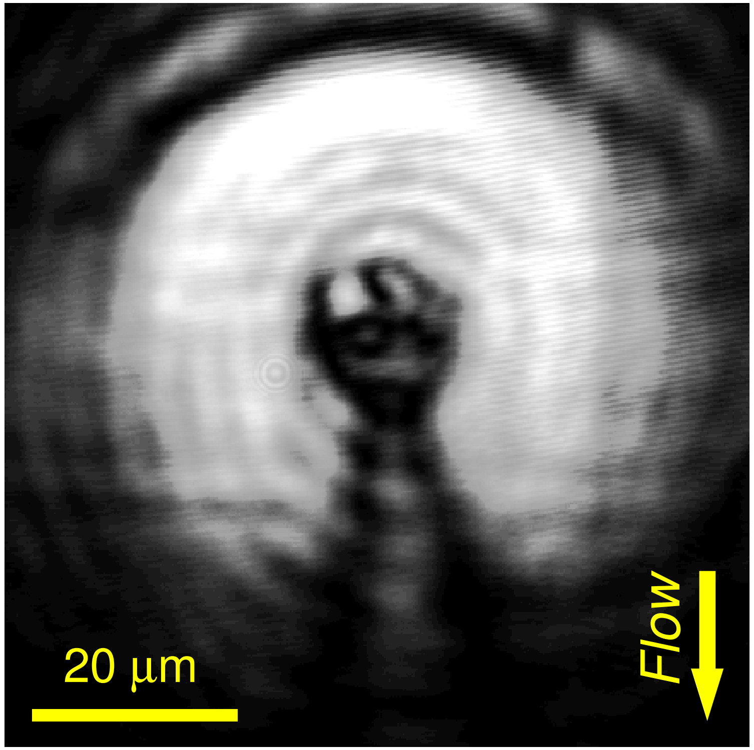
new components



Science **332**, 1167 (2011)

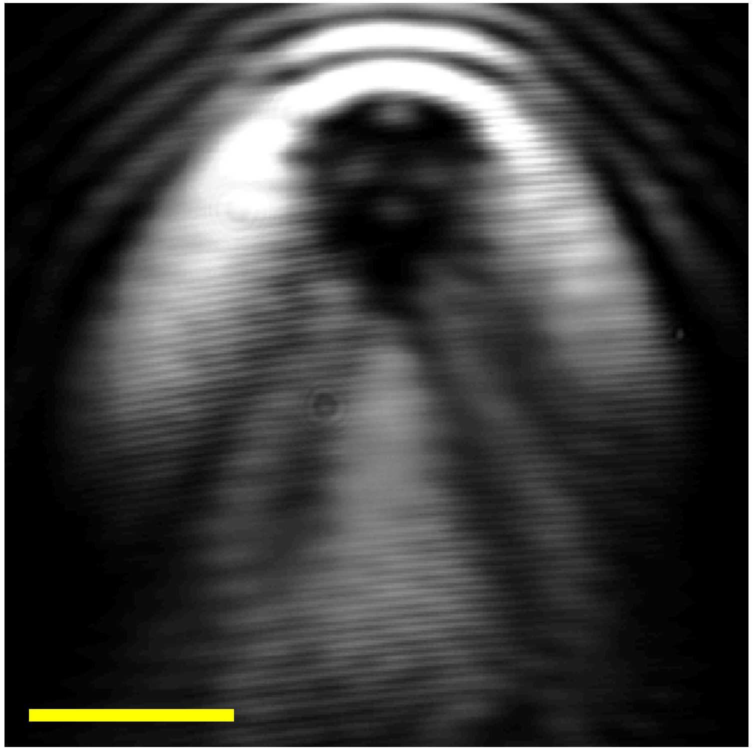
Hydrodynamic soliton multiplets

$k = 0.2\ \mu m^{-1}$



Subsonic

$k = 1.1\ \mu m^{-1}$



Supersonic

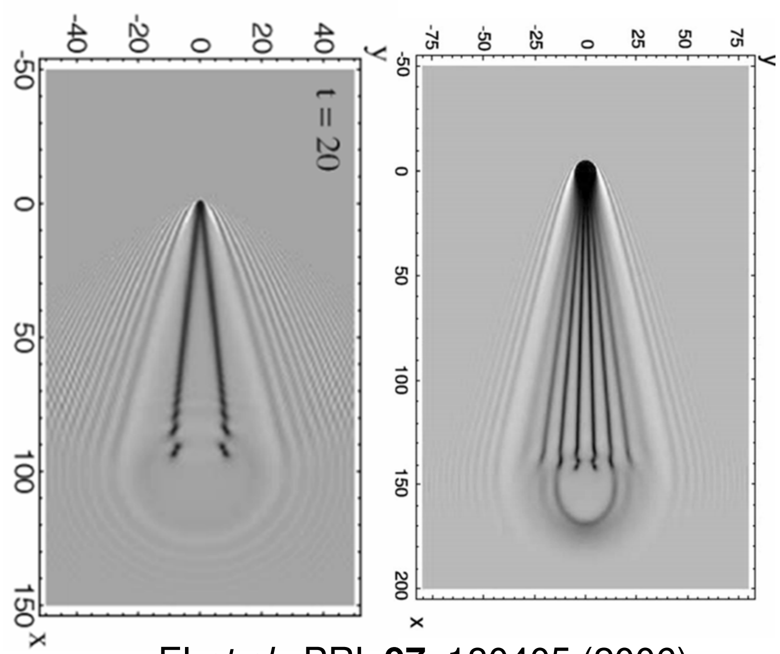
Science **332**, 1167 (2011)

Hydrodynamic soliton multiplets

$k = 0.2\ \mu m^{-1}$

$k = 1.1\ \mu m^{-1}$

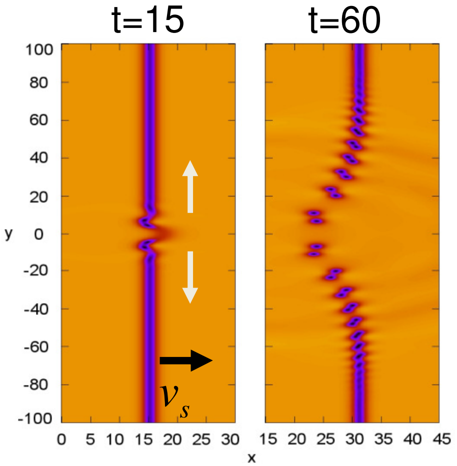
Atomic condensates (GPE theory)



El *et al.*, PRL **97**, 180405 (2006)

Soliton stability

- Solitons in a 2D fluid at rest are unstable: snake unstability

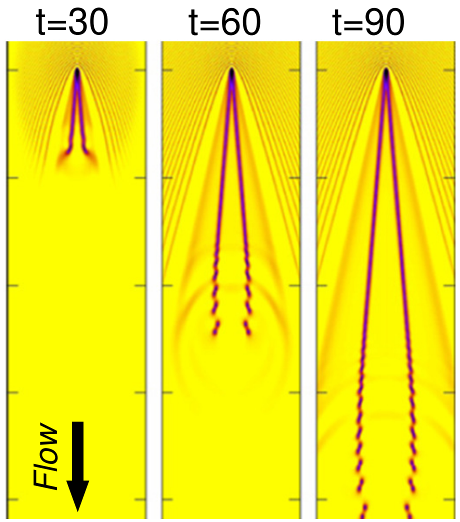


Kamchatnov & Korneev, Phys. Lett. A **375**, 2577 (2011)
Ginsberg *et al.*, PRL **94,** 040403 (2005)
Anderson *et al.*, PRL **86**, 2926 (2001)

$$E_s \sim c_s n \left(1 - \frac{v_s^2}{c_s^2}\right)^{3/2}$$

$$v_s \uparrow \Rightarrow E_s \downarrow \quad depth_s \downarrow$$

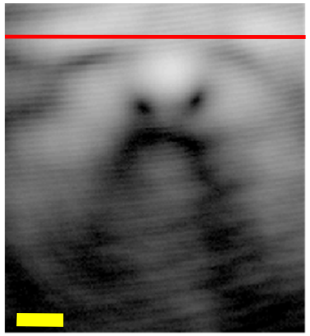
- In a flowing atomic condensate: instability is drifted away (stable solitons)



Atoms

$$v_f > 1.4 c_s$$

Kamchatnov & Korneev, Phys. Lett. A **375**, 2577 (2011)
El *et al.*, PRL **97**, 180405 (2006)
Kamchatnov & Pitaevskii, PRL **100**, 160402 (2008)



Polaritons

$$v_f \sim 0.6 c_s$$

Related experiments: Grosso, et al., PRL **107**, 245301 (2011)

- Polariton decay stabilises the soliton further downflow

A. Kamchatnov & N. Pavloff (private communication)

Polariton spin

- Spin : electron : ±1/2
  hole : ±3/2

Exciton : $J_z = \pm 1$ e ↑↓ h e ↓↑ h

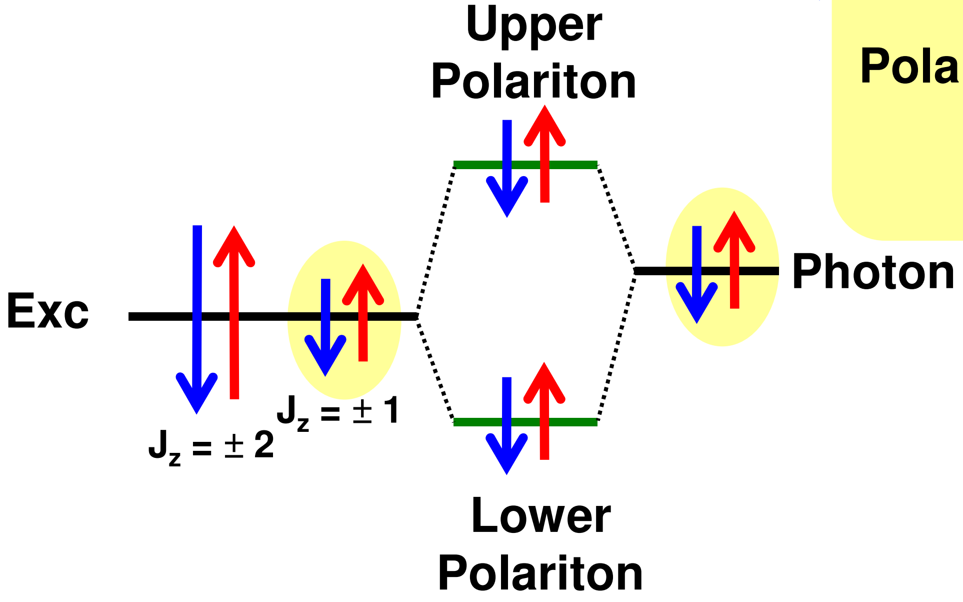
$J_z = \pm 2$ e ↑↑ h e ↓↓ h

- Photons have an angular momentum : ±1

- Only J=1 excitons are coupled to light

Polaritons have two spin projections:

$$\left.\begin{array}{ll} \mathbf{s_z = +1} & \sigma+ \\ \mathbf{s_z = -1} & \sigma- \end{array}\right\} \tfrac{1}{2} \text{ pseudospin}$$



Upper Polariton

Exc

Photon

$\mathbf{J_z = \pm 2}$

$\mathbf{J_z = \pm 1}$

Lower Polariton

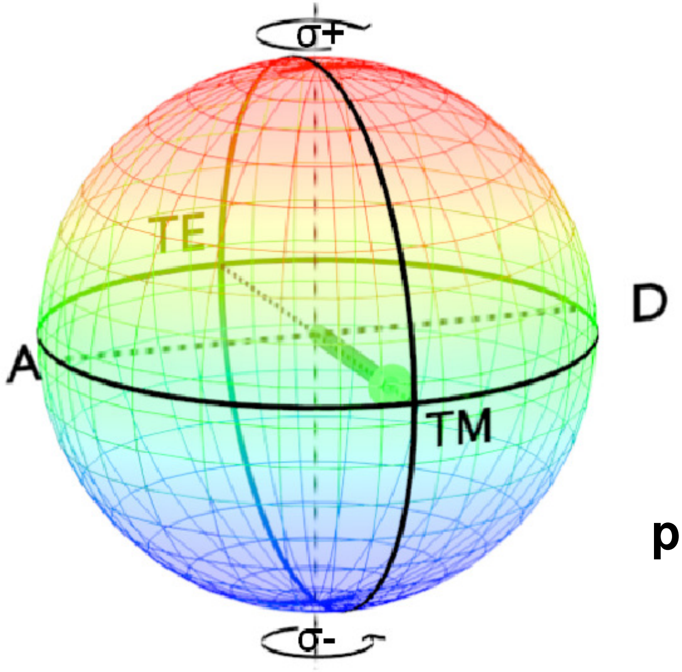
Polariton spin

- Spin : electron : ±1/2
  hole : ±3/2

Exciton : $J_z = \pm 1$ e ↑↓ h e ↓↑ h

$J_z = \pm 2$ e ↑↑ h e ↓↓ h

- Photons have an angular momentum : ±1



- Only J=1 excitons are coupled to light

Polaritons have two spin projections:

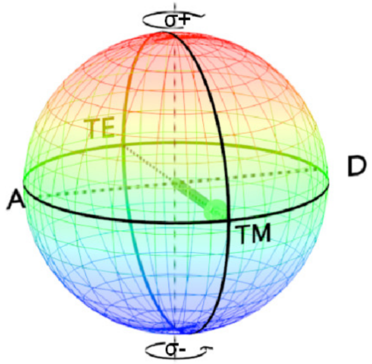
s_z = +1 $\sigma +$
s_z = -1 $\sigma -$
} ½ pseudospin

One-to-one relationship between pseudospin state and polarisation degree

Polariton fluids: spin

Polaritons have two spin projections:

$$\left.\begin{array}{ll} s_z = +1 & \sigma + \\ s_z = -1 & \sigma - \end{array}\right\} \tfrac{1}{2}\ \text{pseudospin}$$



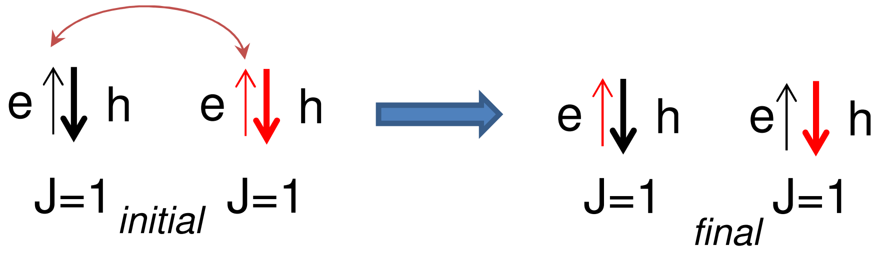
One-to-one relationship between pseudospin state and polarisation degree

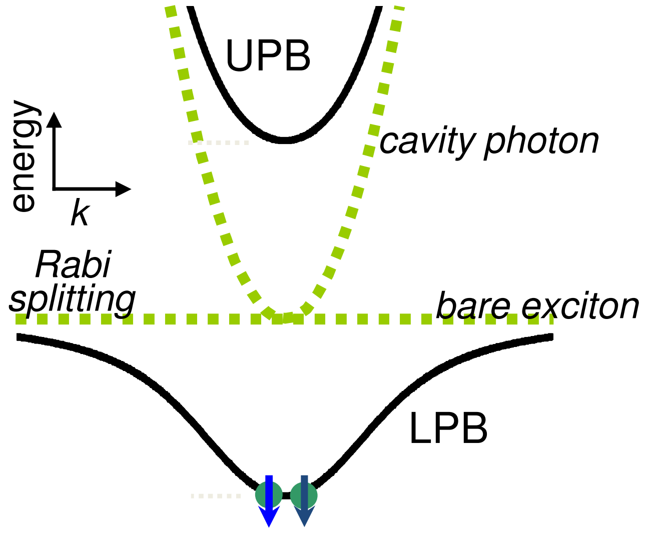
(Strongly) spin-dependent polariton-polariton interactions

non-linear spin phenomena

- Exciton-exciton interaction dominated by **exchange interaction**

Parallel spins (resonant):





Polariton fluids: spin

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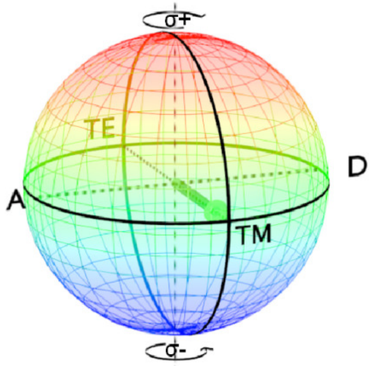

One-to-one relationship between pseudospin state and polarisation degree

- **(Strongly) spin-dependent polariton-polariton interactions**

non-linear spin phenomena

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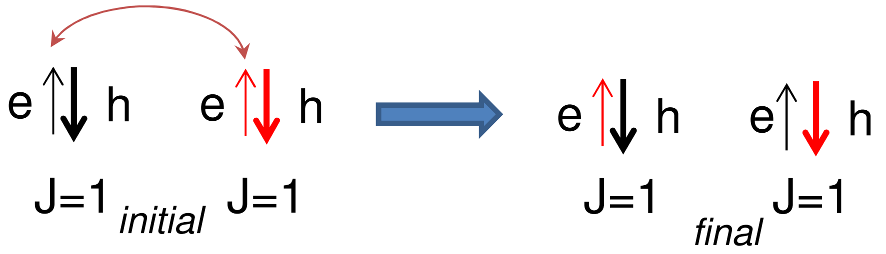
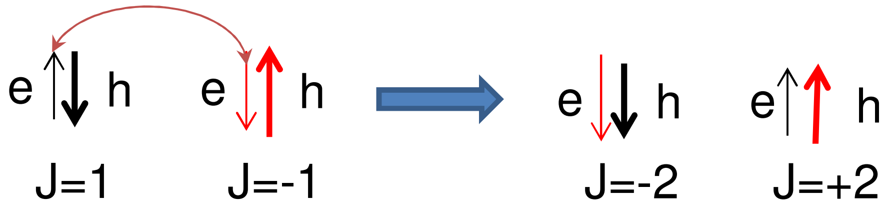
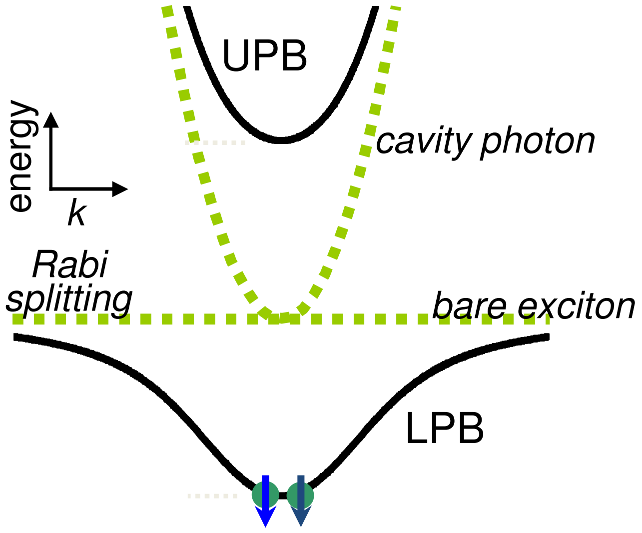
Parallel spins (resonant):



Opposite spins (non-resonant):

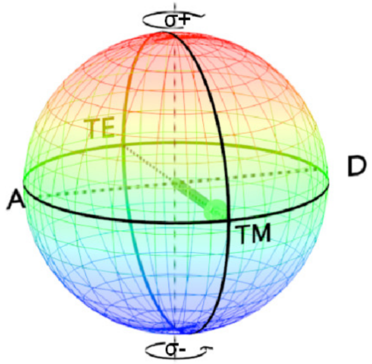




Polariton fluids: spin

- **Polaritons have two spin projections:**

$$\left.\begin{array}{ll} \mathbf{s_z = +1} & \sigma+ \\ \mathbf{s_z = -1} & \sigma- \end{array}\right\} \tfrac{1}{2}\ \text{pseudospin}$$



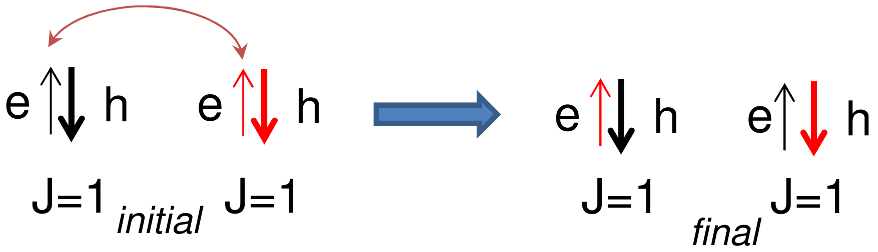
One-to-one relationship between pseudospin state and polarisation degree

- **(Strongly) spin-dependent polariton-polariton interactions**

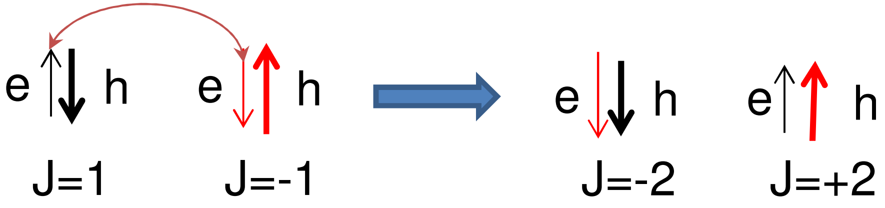
non-linear spin phenomena

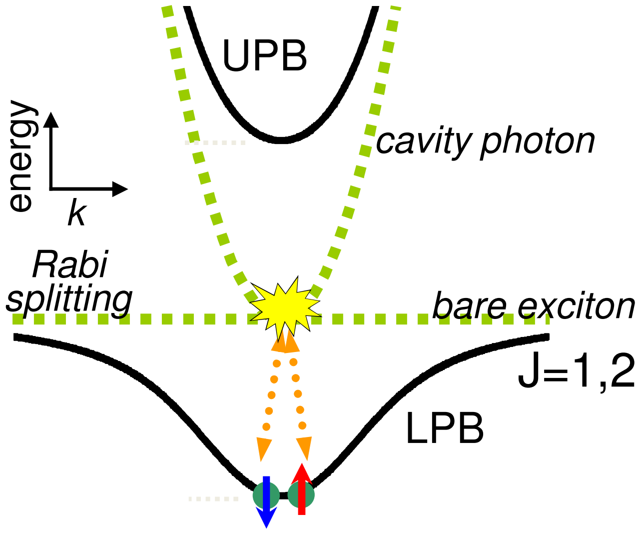
- Exciton-exciton interaction dominated by **exchange interaction**

Parallel spins (resonant):



Opposite spins (non-resonant):



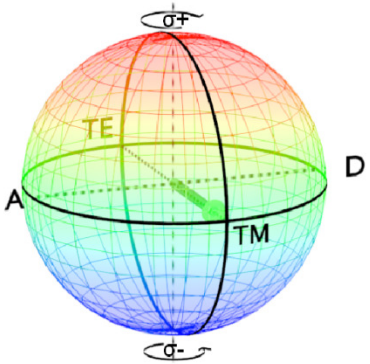


Wouters, PRB **76**, 045319 (2007)
Schumacher *et al.*, PRB **76**, 245324 (2007)

Polariton fluids: spin

Polaritons have two spin projections:

$$\left.\begin{array}{ll} s_z = +1 & \sigma + \\ s_z = -1 & \sigma - \end{array}\right\} \tfrac{1}{2}\ \text{pseudospin}$$



One-to-one relationship between pseudospin state and polarisation degree

(Strongly) spin-dependent polariton-polariton interactions

non-linear spin phenomena

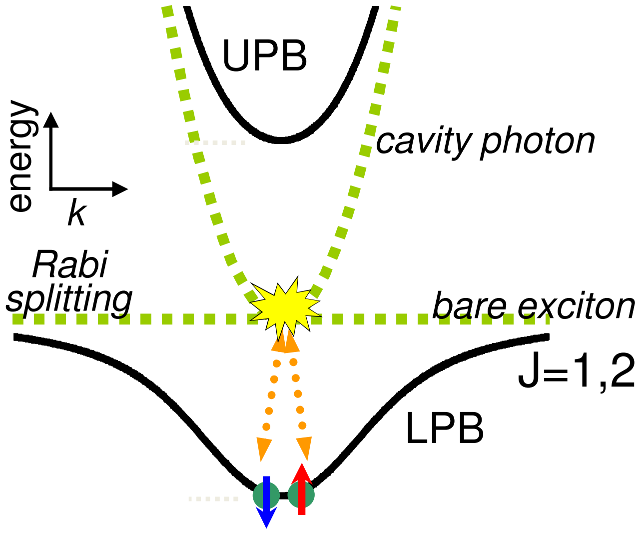
- Exciton-exciton interaction dominated by **exchange interaction**

Parallel spin ($g_{11} = g_{22}$): resonant process

Anti-parallel (g_{12}): via dark exciton intermediate states

$$\boxed{g_{11} = g_{22} >> |g_{12}|}$$

In contrast to ^{87}Rb: $g_{11} \approx g_{22} \approx g_{12}$



Wouters, PRB **76**, 045319 (2007)
Schumacher *et al.*, PRB **76**, 245324 (2007)

Polariton fluids: spin

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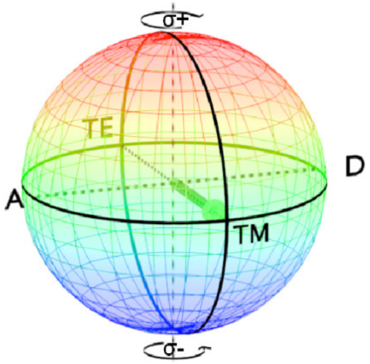


One-to-one relationship between pseudospin state and polarisation degree

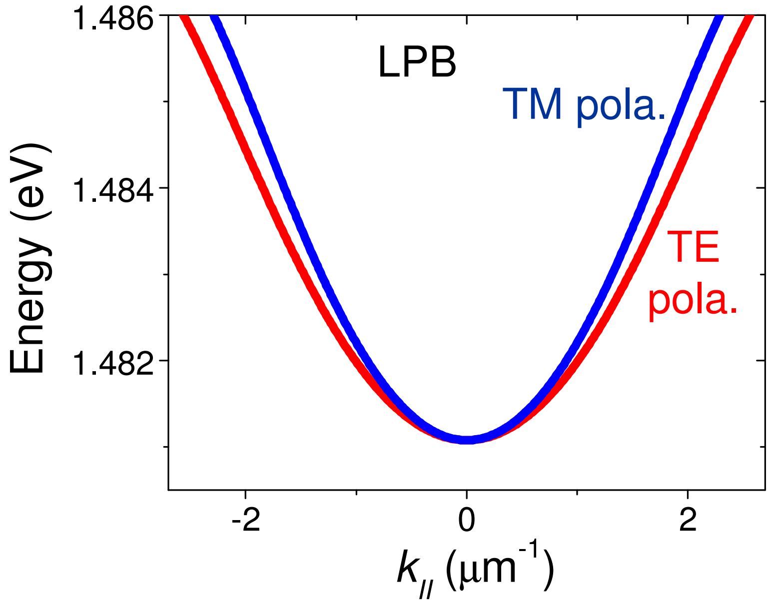
- **(Strongly) spin-dependent polariton-polariton interactions**

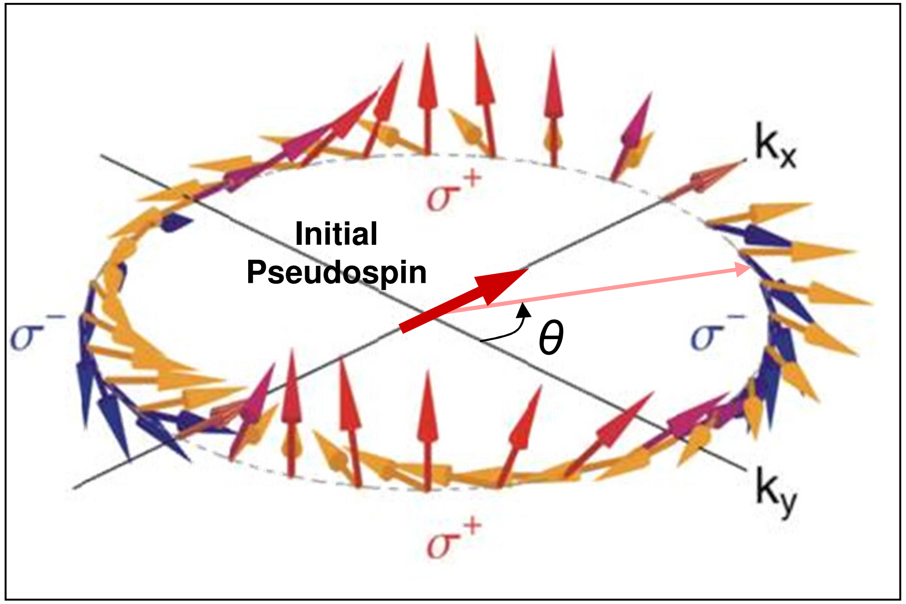
non-linear spin phenomena

- **Intrinsic effective magnetic field**

cavity TE-TM splitting

Effective magnetic field





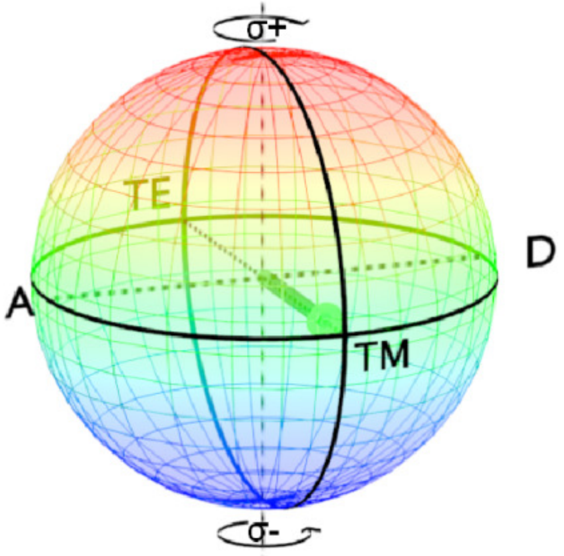
TE-TM splitting characteristic of dielectric cavities

↓

Effective magnetic field acting on the polariton pseudospin

↓

pseudospin precession

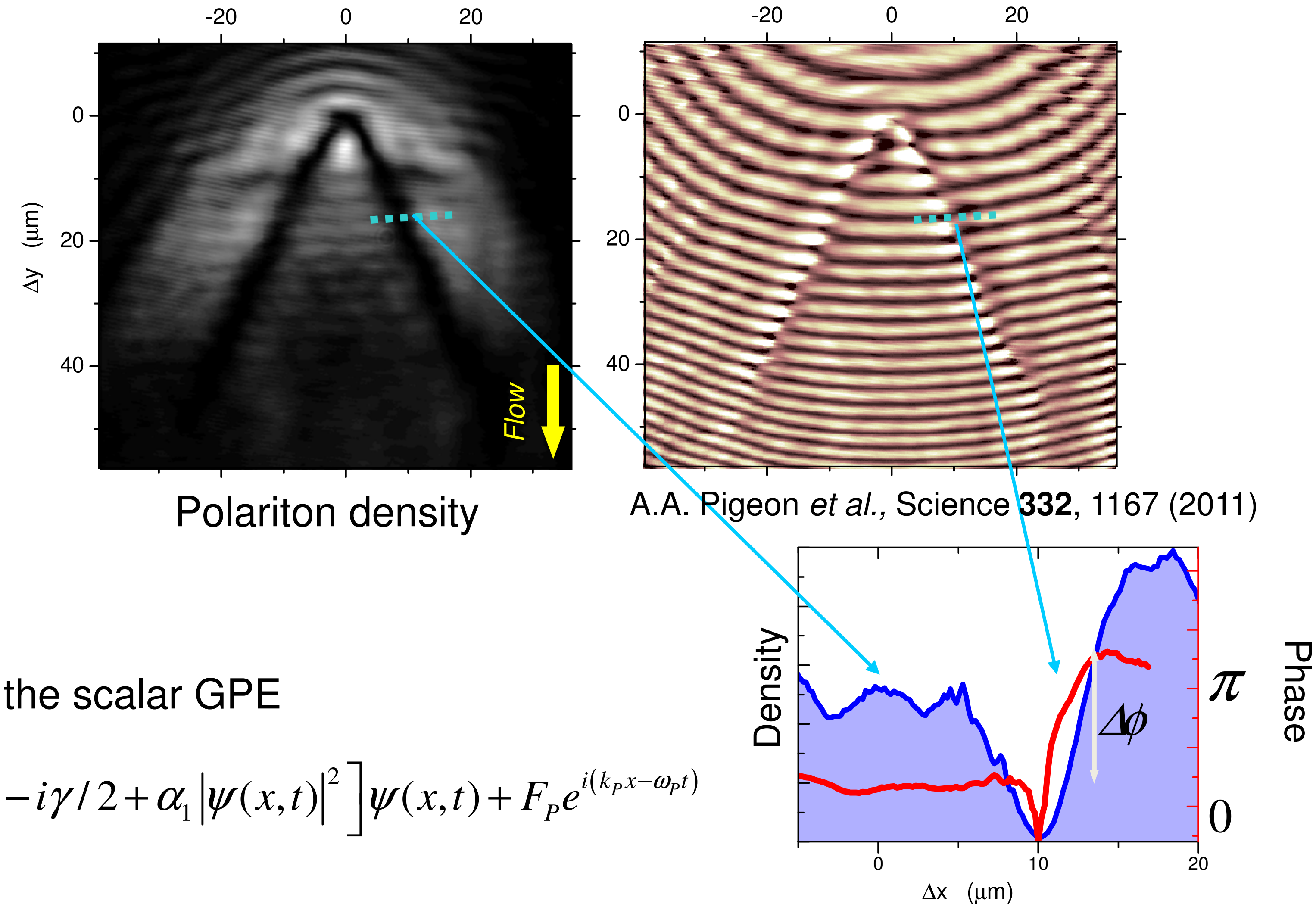


Hydrodynamic scalar solitons

- Resonant excitation: supersonic flow
- σ+ fluid : scalar dark solitons

v_f = 1.7 µm/ps
k = 0.73 µm^{-1}

High speed



Polariton density

A.A. Pigeon *et al.*, Science **332**, 1167 (2011)

- Solution of the scalar GPE

$$i\partial_t\psi(x,t) = \left[D - i\gamma/2 + \alpha_1\left|\psi(x,t)\right|^2\right]\psi(x,t) + F_P e^{i(k_P x-\omega_P t)}$$

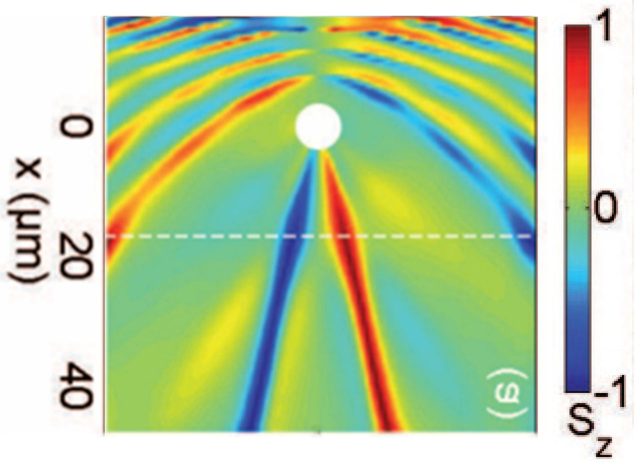
Spinor polariton fluid: half solitons

- Linearly polarised injection (50% s_z=+1, 50% s_z=-1)

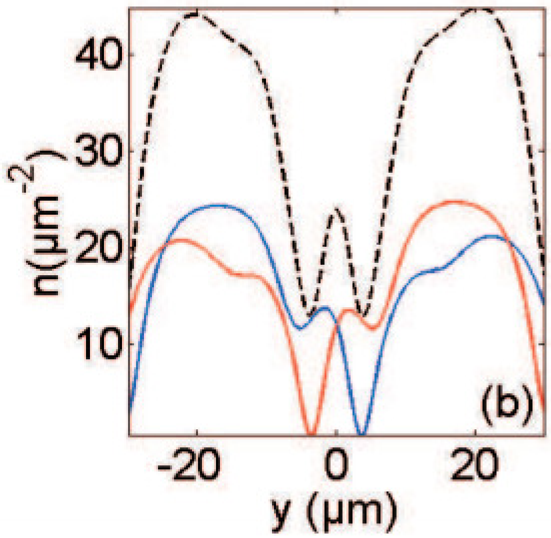
$$
\begin{aligned}
i\hbar\frac{\partial\Psi^{ph}_{\pm}}{\partial t} &= -\frac{\hbar^2}{2m^*_{ph}}\Delta\Psi^{ph}_{\pm} + D_{\pm}\Psi^{ph}_{\pm} + \frac{\Omega_R}{2}\Psi^{ex}_{\pm} \\
&\quad - \frac{i\hbar}{2\tau_{ph}}\Psi^{ph}_{\pm} + P_{\pm} + \boxed{\beta\left(\frac{\partial}{\partial x} \mp i\frac{\partial}{\partial y}\right)^2}\Psi^{ph}_{\mp} \\
i\hbar\frac{\partial\Psi^{ex}_{\pm}}{\partial t} &= -\frac{\hbar^2}{2m^*_{ex}}\Delta\Psi^{ex}_{\pm} + \frac{\Omega_R}{2}\Psi^{ph}_{\pm} \\
&\quad - \frac{i\hbar}{2\tau_{ex}}\Psi^{ex}_{\pm} + \boxed{\left(\alpha_1\left|\Psi^{ex}_{\pm}\right|^2 + \alpha_2\left|\Psi^{ex}_{\mp}\right|^2\right)}\Psi^{ex}_{\pm}
\end{aligned}
$$

TE-TM splitting

Spin-dependent interactions



Flayac et al. PRB **83**, 193305 (2011)



Half-Solitons

Mixed spin-phase topological solitons

Half-solitons: tomography

Linearly polarised injection

Circular polarisation: two fluids

Soliton present in one σ component only (for example σ+)

change of basis

$$\sigma+ \;\longrightarrow\; \psi_+ \sim e^{i\theta_+} \qquad \Delta\theta_+ \approx \pi$$

$$\sigma- \;\longrightarrow\; \psi_- \sim e^{i\theta_-} \qquad \Delta\theta_- \approx 0$$

across the half-soliton

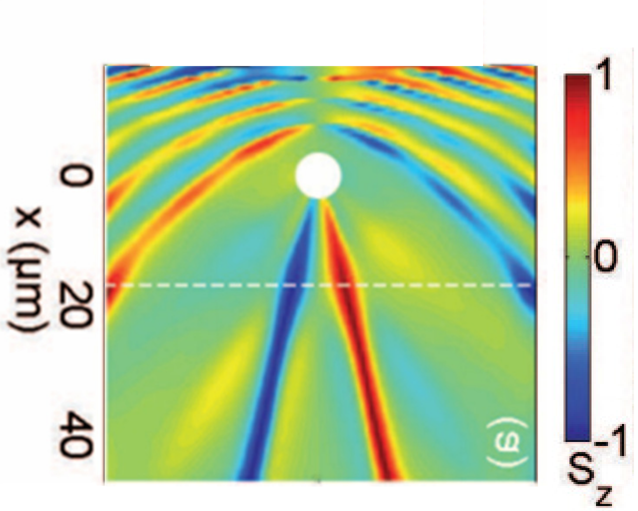
Linear polarisation

$$D \;\longrightarrow\; \psi_D \sim \cos(\eta)e^{i\varphi} \qquad \eta = \frac{\theta_+ - \theta_-}{2}$$

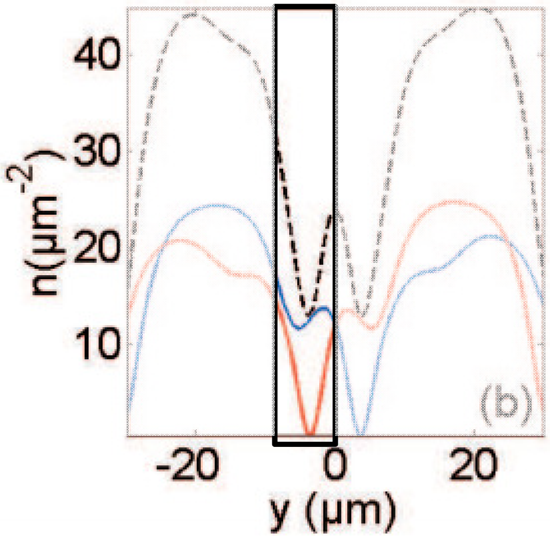
polarisation direction

$$AD \;\longrightarrow\; \psi_{AD} \sim \sin(\eta)e^{i\varphi} \qquad \phi = \frac{\theta_+ + \theta_-}{2}$$

global phase



Flayac et al. PRB **83**, 193305 (2011)



Half-solitons: tomography

Linearly polarised injection

- **Circular polarisation**: two fluids

Soliton present in one σ component only (for example σ+)

change of basis

$$\sigma+ \;\longrightarrow\; \psi_+ \sim e^{i\theta_+}$$

$$\sigma- \;\longrightarrow\; \psi_- \sim e^{i\theta_-}$$

$$\left.\begin{array}{l}\Delta\theta_+ \approx \pi \\ \Delta\theta_- \approx 0\end{array}\right\}$$ across the half-soliton

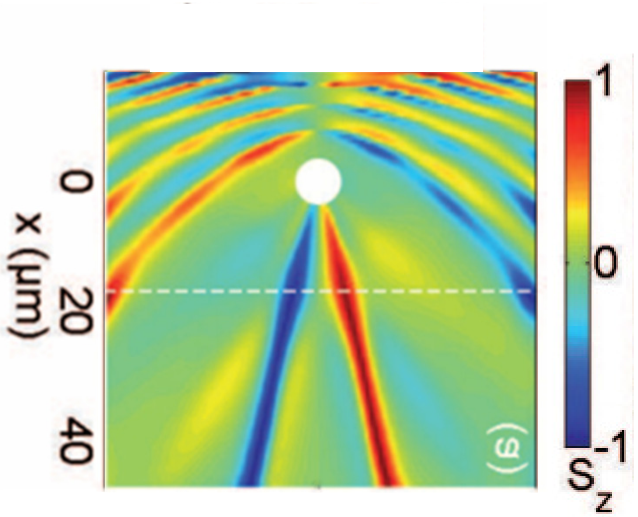
- **Linear polarisation**

$$D \;\longrightarrow\; \psi_D \sim \cos(\eta)\, e^{i\varphi}$$

$$AD \;\longrightarrow\; \psi_{AD} \sim \sin(\eta)\, e^{i\varphi}$$

$$\eta = \frac{\theta_+ - \theta_-}{2}$$ polarisation direction

$$\phi = \frac{\theta_+ + \theta_-}{2}$$ global phase



Flayac et al. PRB **83**, 193305 (2011)

Across the half-soliton:

$$\Delta\eta \approx \pi/2$$ Polarisation rotation of 90º

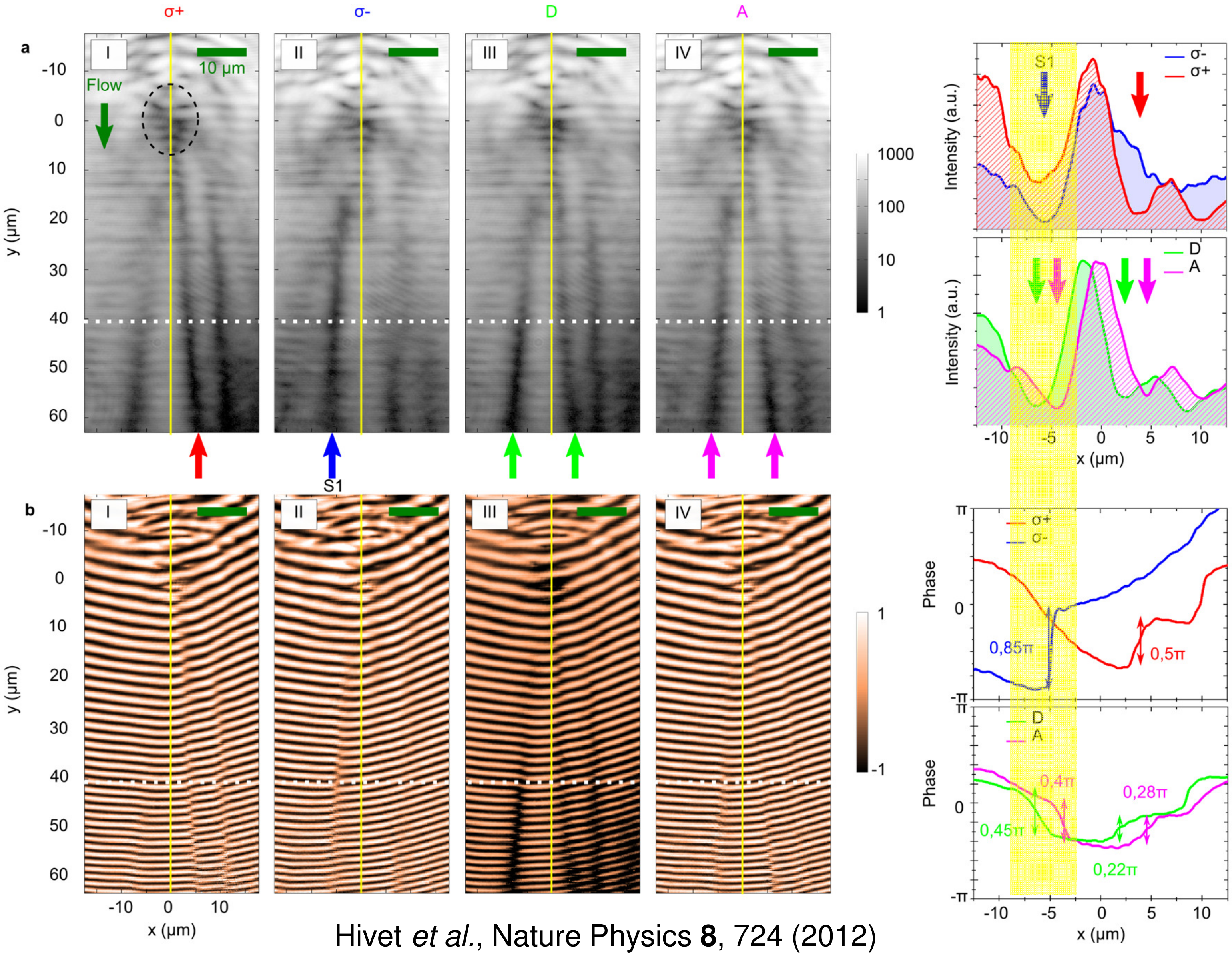
$$\Delta\varphi \approx \pi/2$$ half phase jump

structure similar to that of half-vortices

Rubo, PRL **99**, 106401 (2007)
Lagoudakis *et al.*, Science **326**, 974 (2009)

Half-solitons: experiment

Circular polarisation Linear polarisation



$$\Delta\eta \approx \pi/2$$

$$\Delta\theta_+ \approx \pi$$

$$\Delta\theta_- \approx 0$$

$$\Delta\varphi \approx \pi/2$$

Hivet *et al.*, Nature Physics **8**, 724 (2012)

Half-solitons: experiment

- Polarisation tomography

Circular basis

$$\Delta\theta_+ \approx \pi$$
$$\Delta\theta_- \approx 0$$

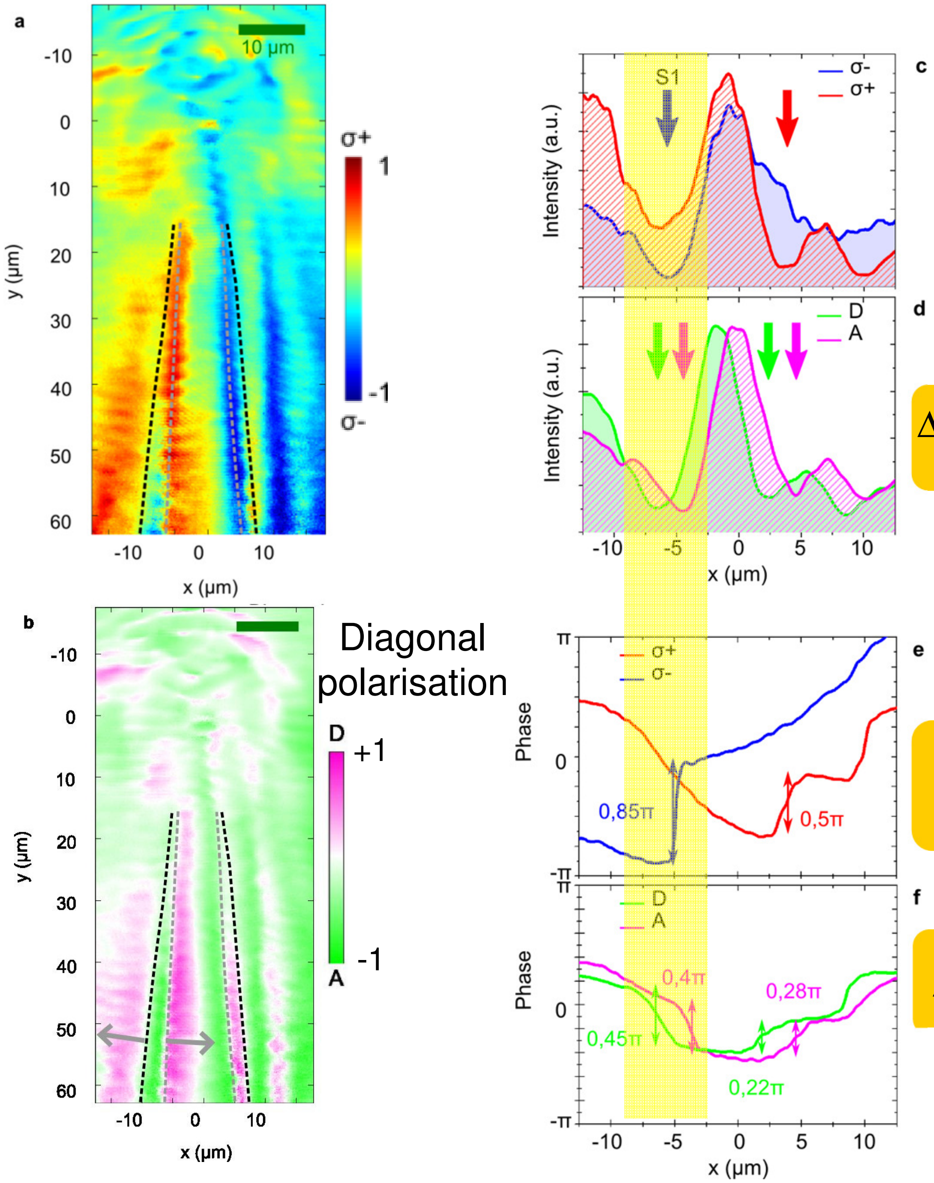
$$\eta = \frac{\theta_+ - \theta_-}{2} \qquad \phi = \frac{\theta_+ + \theta_-}{2}$$

$$\Delta\eta \approx \pi/2$$
$$\Delta\varphi \approx \pi/2$$

Linear basis

Polarisation domain wall

Circular polarisation



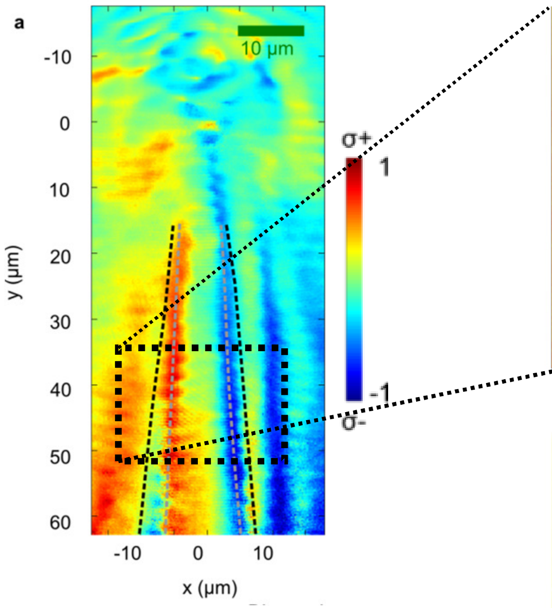
Diagonal polarisation

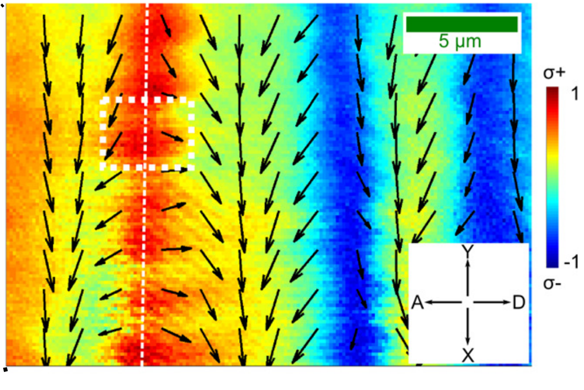
$$\Delta\eta \approx \pi/2$$

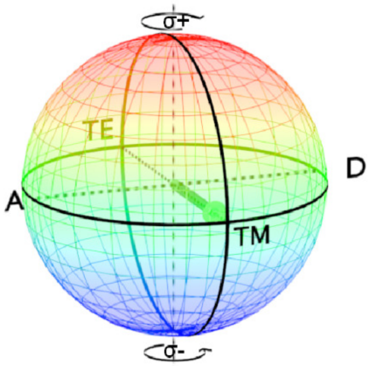
$$\Delta\theta_+ \approx \pi$$
$$\Delta\theta_- \approx 0$$

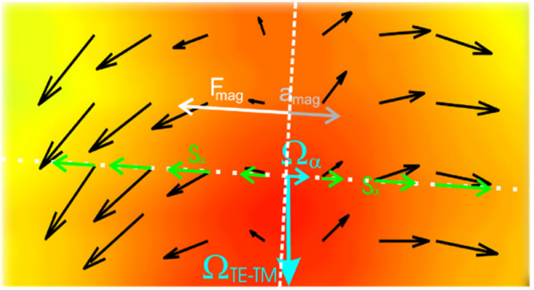
$$\Delta\varphi \approx \pi/2$$

Half-solitons: 1D monopoles



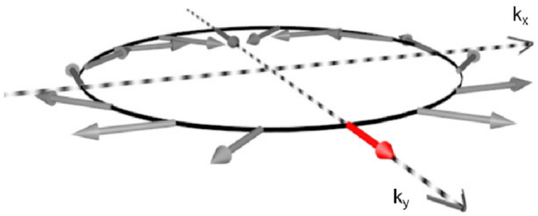






Divergent spin texture

point charge



Magnetic field (TE-TM)

Magnetic energy

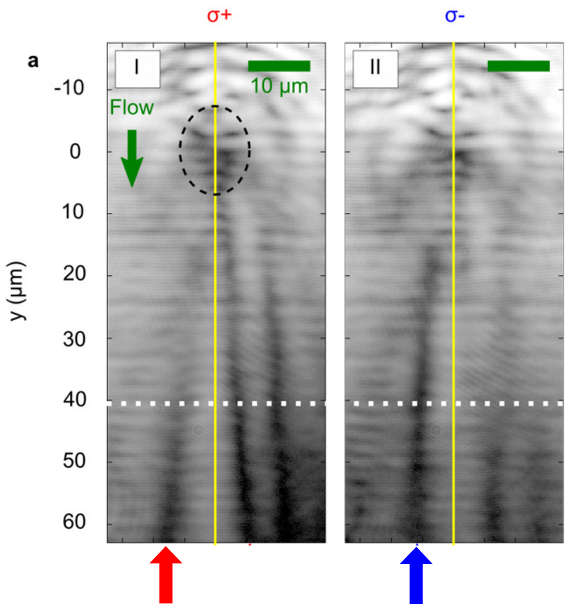
$$\int -\vec{S}\left(x'-x_0\right)\cdot\vec{\Omega}_{TE-TM}\,dx' \quad \begin{array}{ll} >0 & \text{to the left} \\ <0 & \text{to the right} \end{array}$$

$\Downarrow$

Force towards the left $\xrightarrow[m<0]{}$ acceleration to the right

Magnetic monopole-like

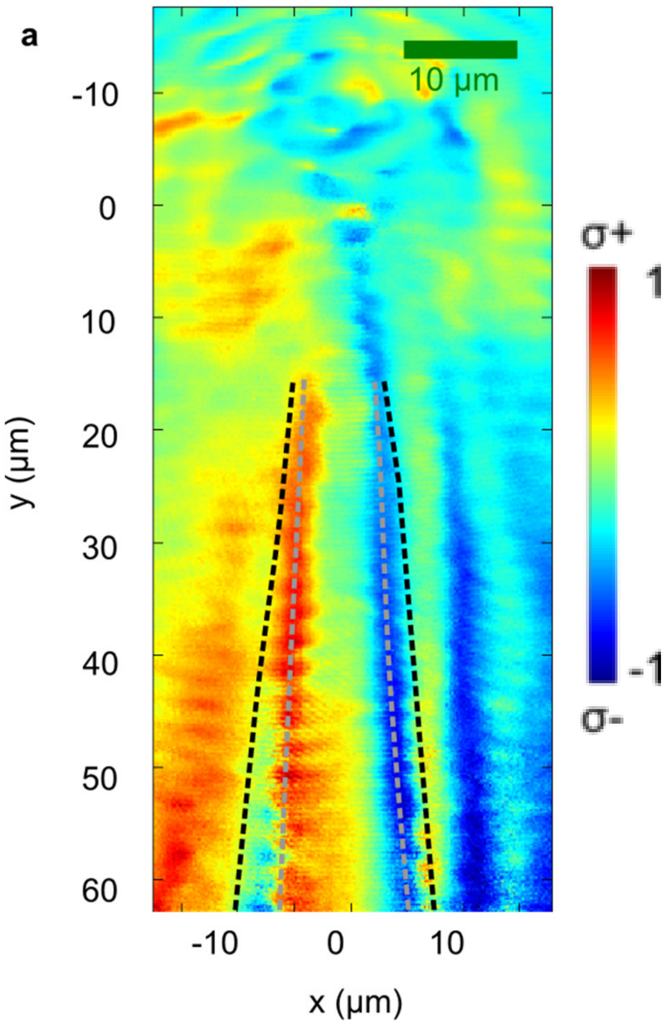
Half-solitons: 1D monopoles



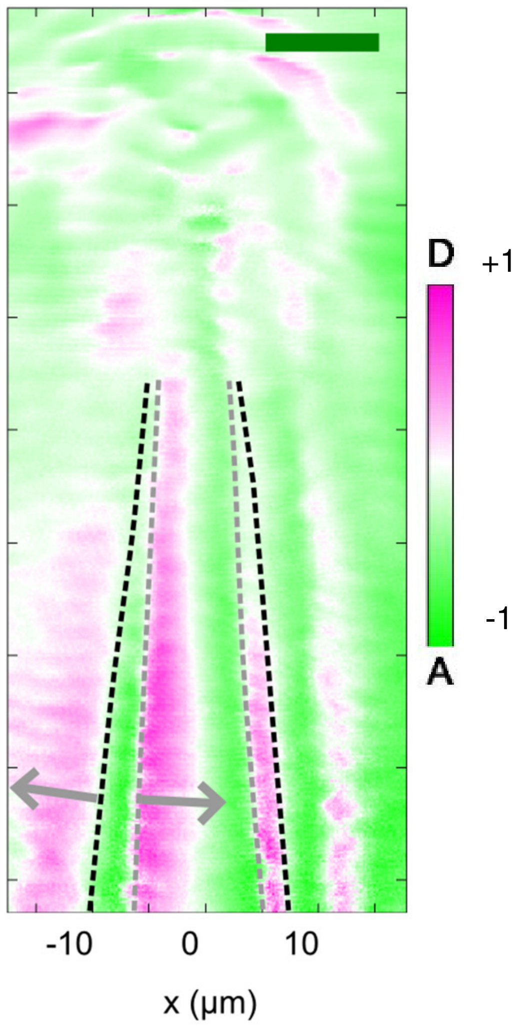
Monopoles of opposite "charge"

spatial separation

Circular polarisation



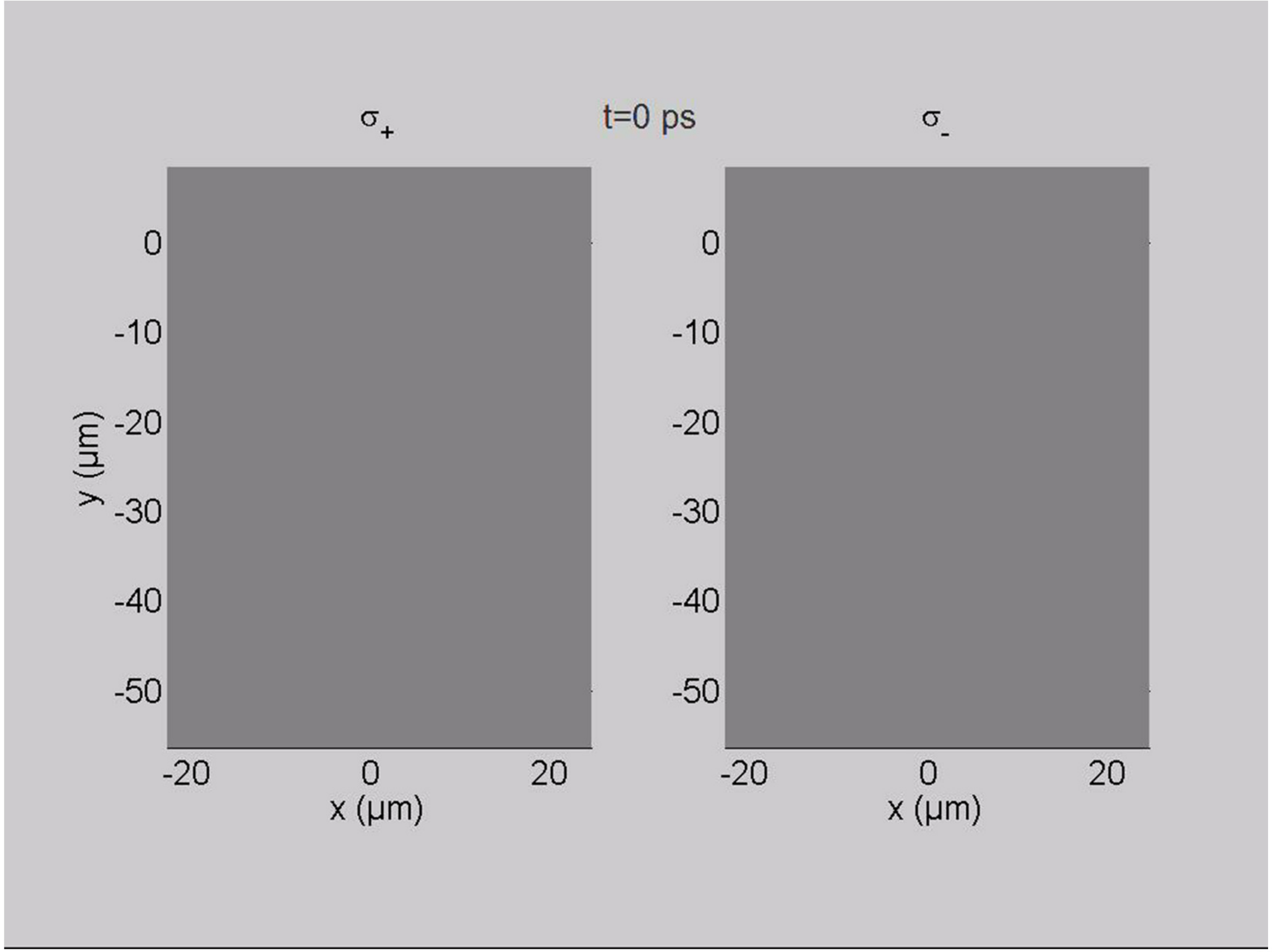
Diagonal polarisation



Hivet *et al.*, Nature Physics **8**, 724 (2012)

Half-solitons: 1D monopoles

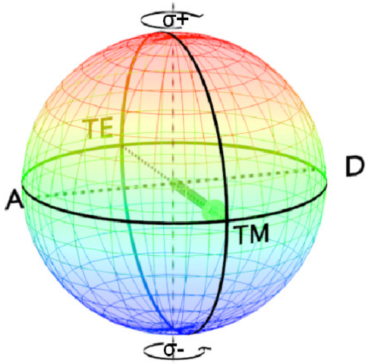
- Simulation



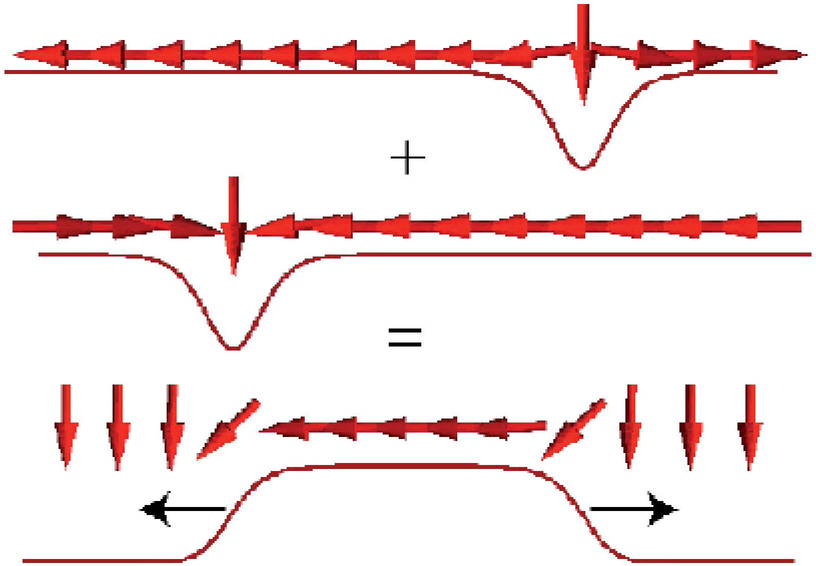
Coulomb-like interaction

- **Arises from the spin-dependent interactions**

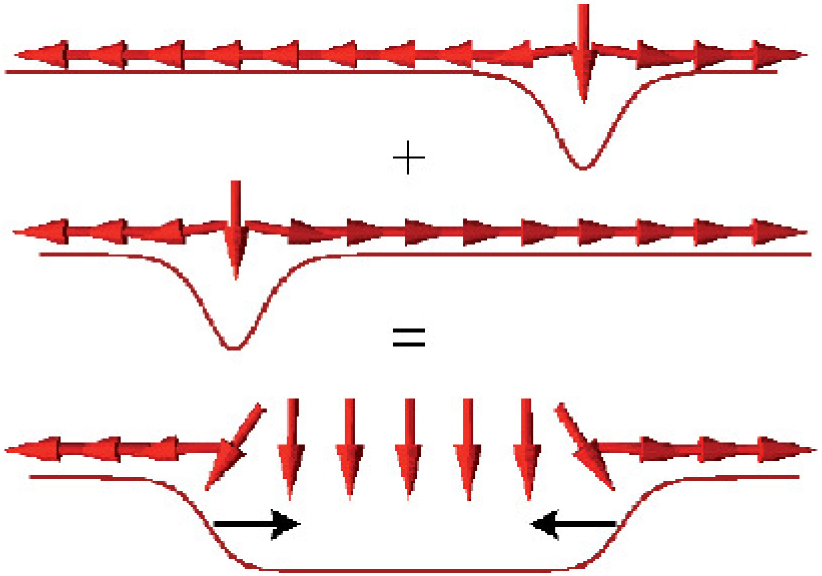
$$g_{11} = g_{22} \gg |g_{12}|$$



- **Minimise energy: in-plane pseudospin**



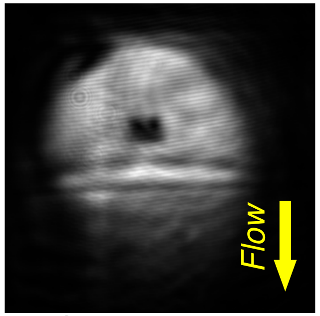
Opposite effective charges REPEL



Same effective charges ATRACT

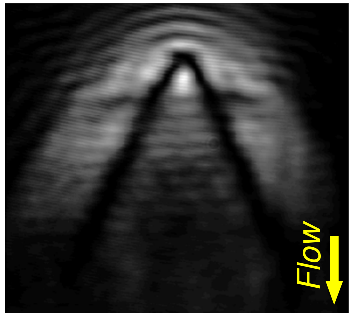
Summary

Scalar solitons and vortices: hydrodynamics



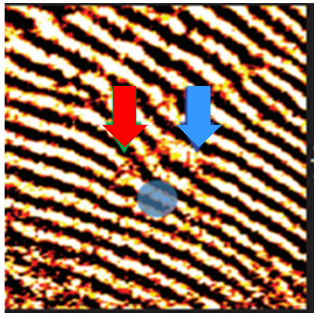
Superflow

Nature Physics **5**, 805 (2009)



Oblique dark solitons

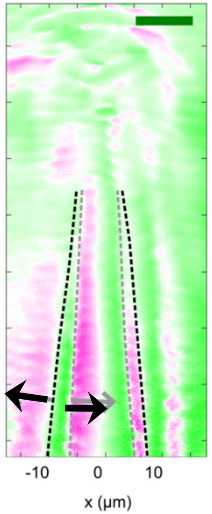
Science **332**, 1167 (2011)



Hydrodynamic vortices

Nature Phot. **5**, 610 (2011)

Half-solitons: magnetic-monopole analogues

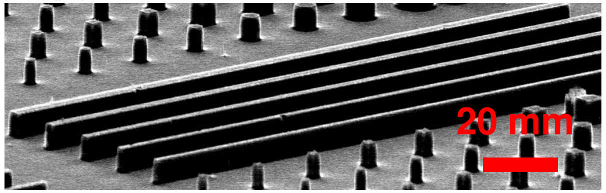


Hivet et al., Nature Phys. **8**, 724 (2012)

Flayac *et al.*, PRB **83**, 193305 (2011)

Solnyshkov *et al.*, PRB **85**, 073105 (2012)

Half-solitons in 1D: Coulomb like interactions



Wertz *et al.*, Nature Phys. **6**, 860 (2010)