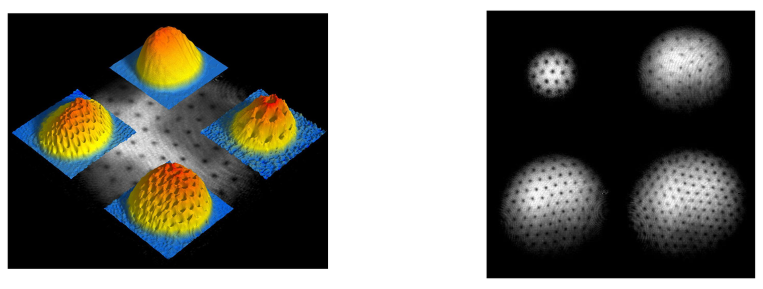
Vortices in quantum fluids

Classical vortices
(e.g. whirlpool, tornado)

When the liquid rotates,
one giant vortex forms

Quantum vortices
(e.g. Bose-Einstein condensates)



Large vortices are energetically
unstable - many small vortices form
The form a triangular lattice or crystal

Therefore in a quantum liquid:

These many small vortices interact and act like particles
-> vortex states of matter - not possible in classical liquids

Our work concerns the theory and experiments of creating
ensembles of quantized vortices in polariton condensates
towards new states of quantum vortex matter.

Ensembles can most successfully be created by rotation or spontaneous excitation

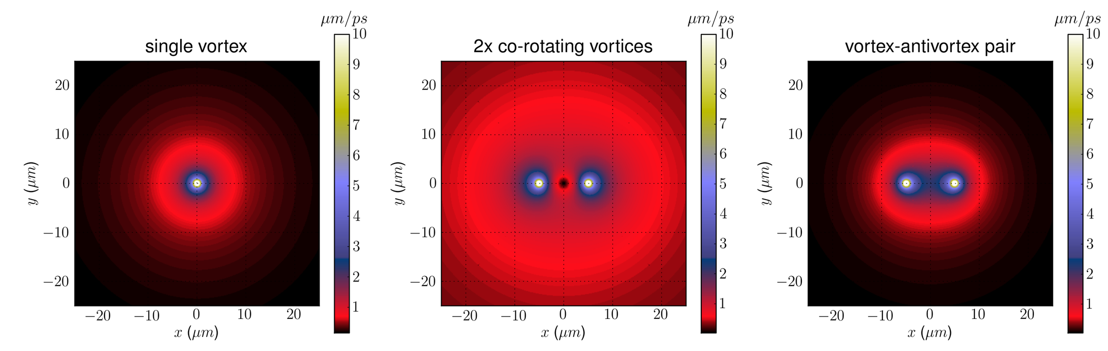
Berezinskii-Kosterlitz-Thouless (BKT) superfluid

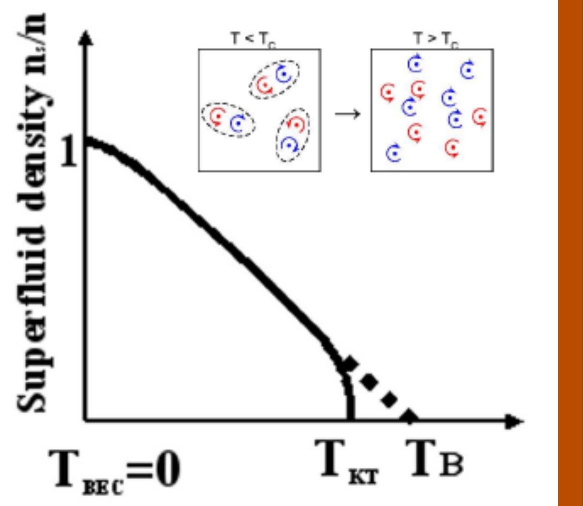
- Pairs of oppositely circulating vortices with energy proportional to separation

$$E_v = \frac{n_C}{2\pi}\frac{\hbar^2}{m_{LP}}\ln\left(\frac{d_v}{\xi}\right)$$

- Lower energy than interacting single vortices
- Usually form in 2D systems by thermal fluctuations
- Represent microscopic nature of the BKT phase transition - phase distortions confined to vortex pairs

Vortex velocity profile:
vortex-antivortex pair less destructive than co-rotating vortices

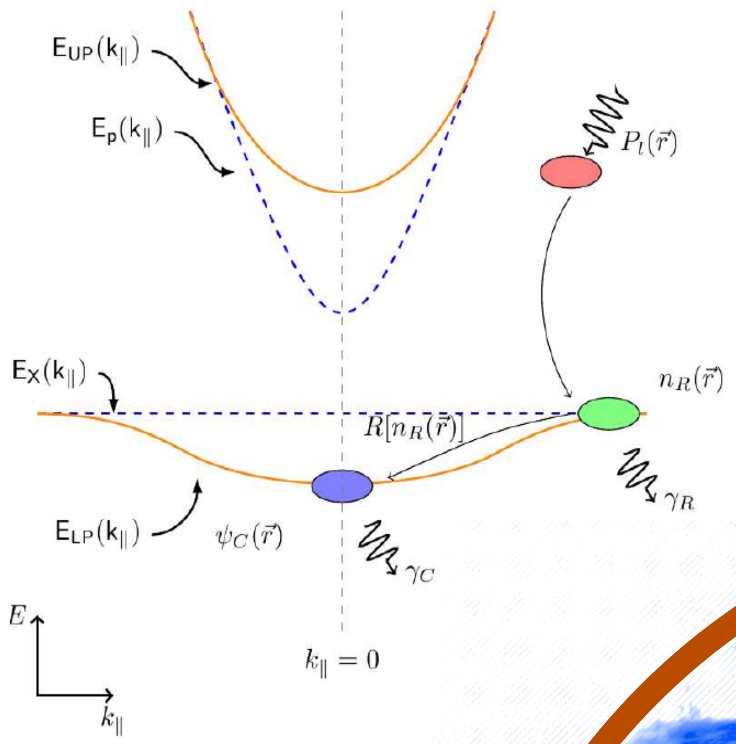




Polariton condensate is strongly dissipative

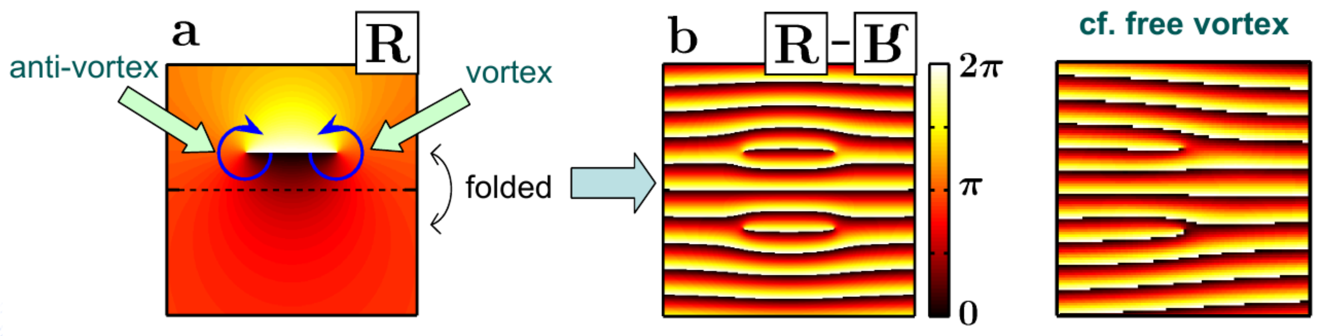
Features of the exciton polariton system

- Strong coupling of exciton and cavity photon modes in a semiconductor microcavity.
- Resulting lower polaritons can be generally treated as a dilute gas of very light repulsively interacting bosons.
- Low mass → high transition temperature
- In-plane momentum is conserved in photon mode
- Condensate forms by stimulated scattering of polaritons from a thermal reservoir - reservoir plays a strong role in condensate dynamics

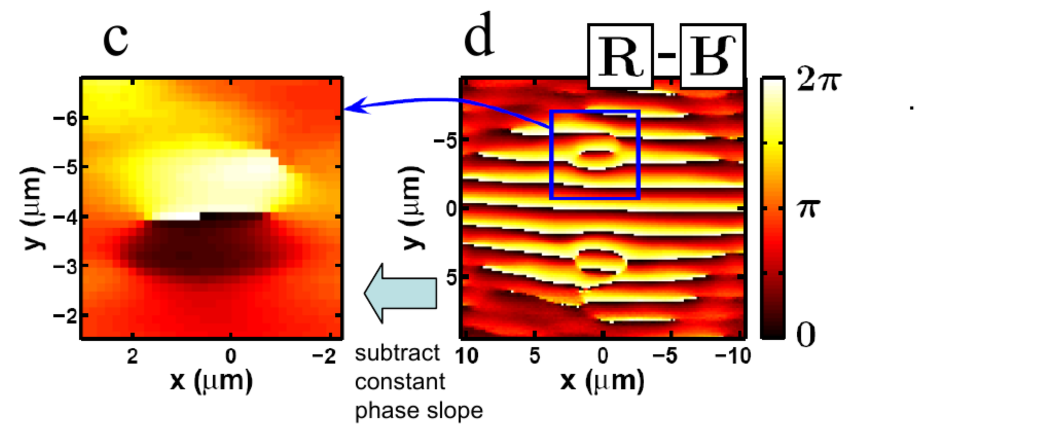


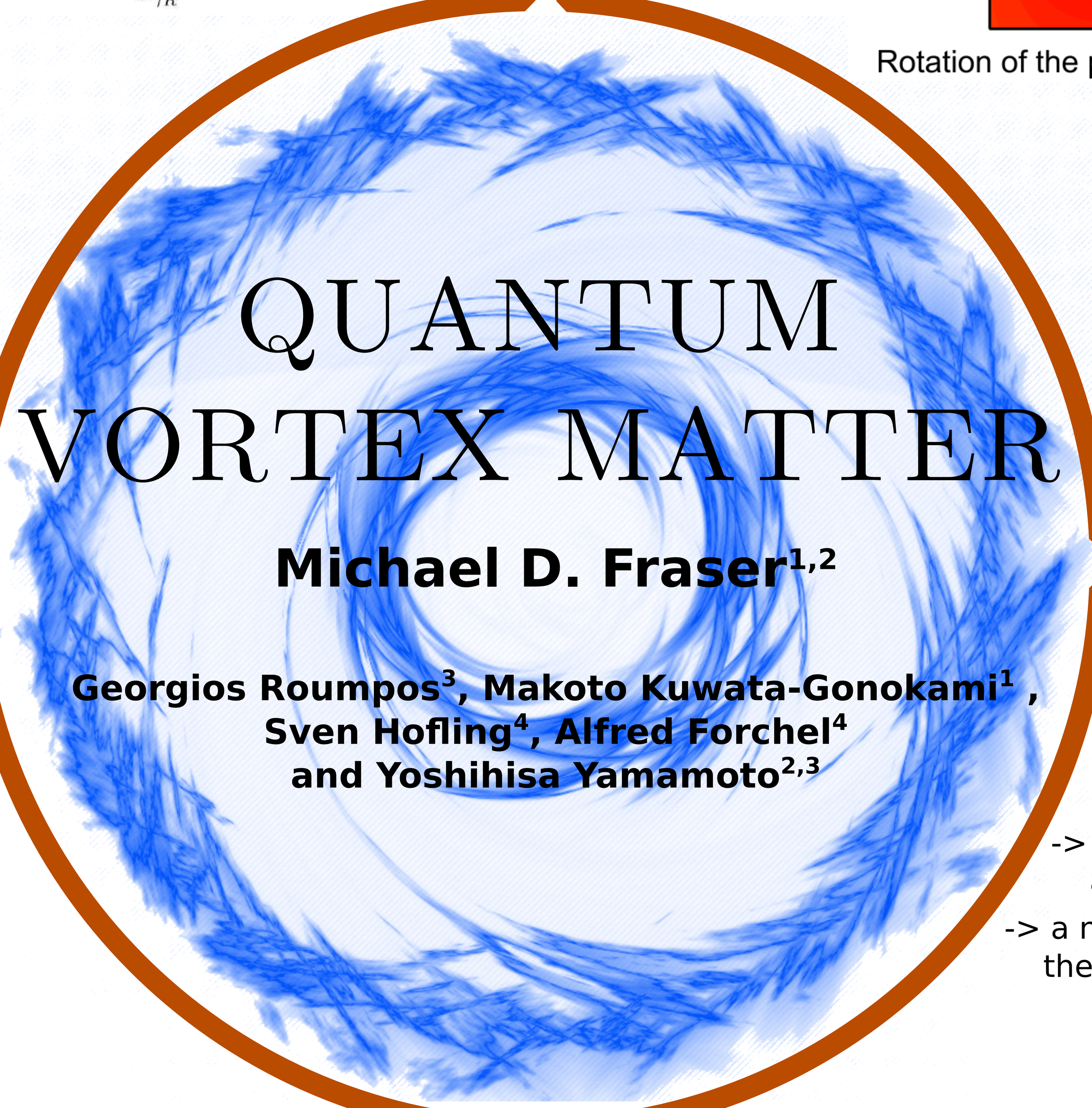
Observation of spontaneous vortex pairs

Single vortex-antivortex pair in an exciton-polariton condensate
Georgios Roumpos, Michael D. Fraser, Andreas Löffler, Sven Höfling, Alfred Forchel & Yoshihisa Yamamoto
Nature Physics (2010) doi:10.1038/nphys1841
Vortex-antivortex pair dynamics in an exciton-polariton condensate
M. D. Fraser, G. Roumpos and Y. Yamamoto,
New Journal of Physics 11 113048 (2009)



Rotation of the phase by 2π around a vortex, and by -2π around an anti-vortex





QUANTUM VORTEX MATTER

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Georgios Roumpos[3], Makoto Kuwata-Gonokami[1], Sven Hofling[4], Alfred Forchel[4] and Yoshihisa Yamamoto[2,3]

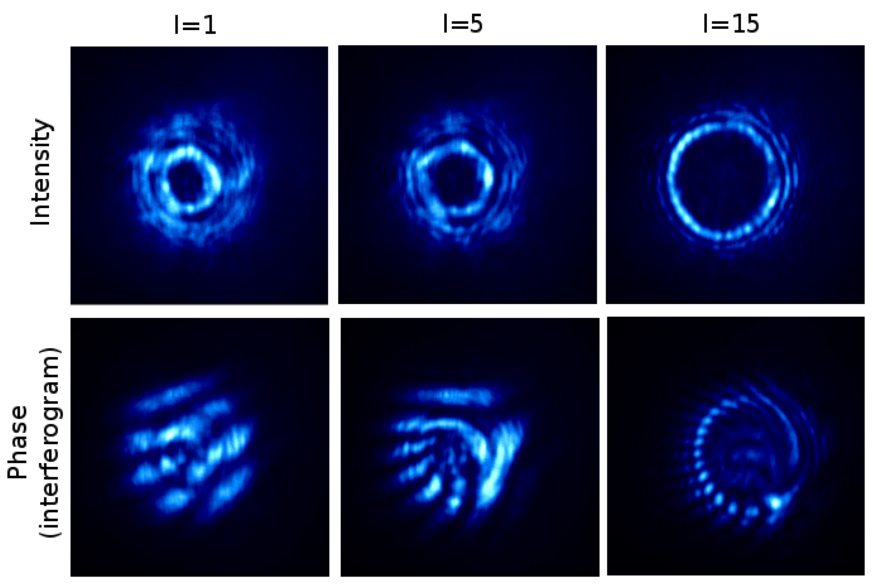
Rotating a polariton condensate

Q: How do you rotate a liquid at a rate of 10^{11} times a second?
A: Stir the liquid with an optical vortex

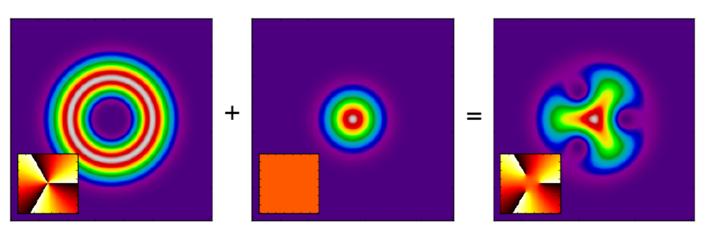
Because light has no interactions, we can make any size or number of vortices

$$\psi_{LG}^{l,p}(\mathbf{r}_\perp, z) = (-1)^p\left(\frac{\sqrt{2}r}{w_0}\right)^l L_p^l\left(\frac{2r^2}{w_0^2}\right) e^{-il\theta} e^{-r^2/w_0^2} e^{-ikz}$$

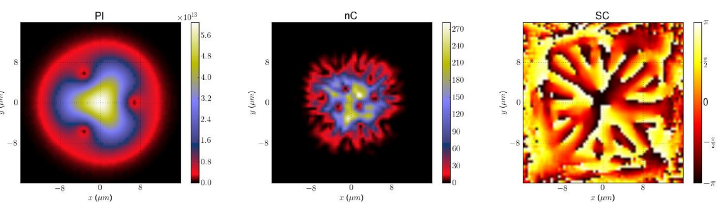
Experimental optical vortices - Laguerre-Gauss modes



Physically rotating laser beam at ~10^{11}Hz



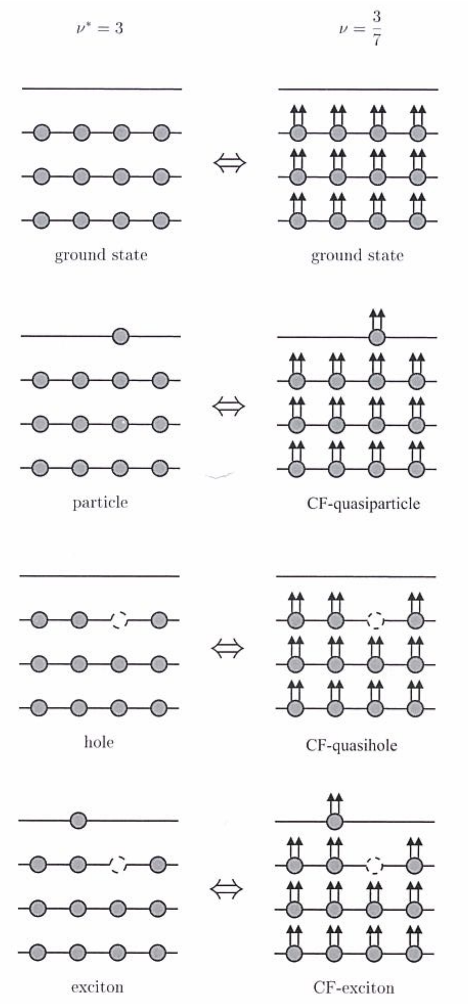
Simulation of resulting condensate vortex formation



Fractional Quantum Hall states

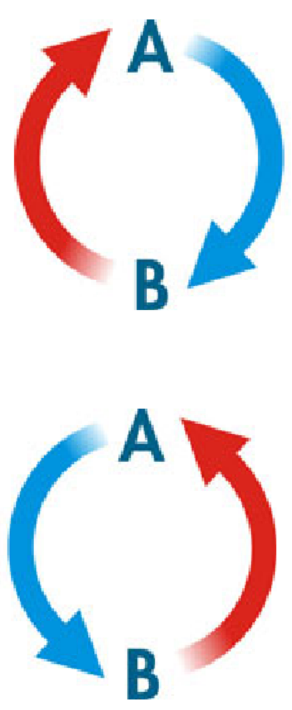
Under very rapid rotation the vortex number
becomes comparable to the polariton number

-> polaritons and vortices combine to form a new composite fermion quasi-particle
-> a new state emerges with similar physics to the electronic fractional quantum Hall liquid



Anyonic statistics

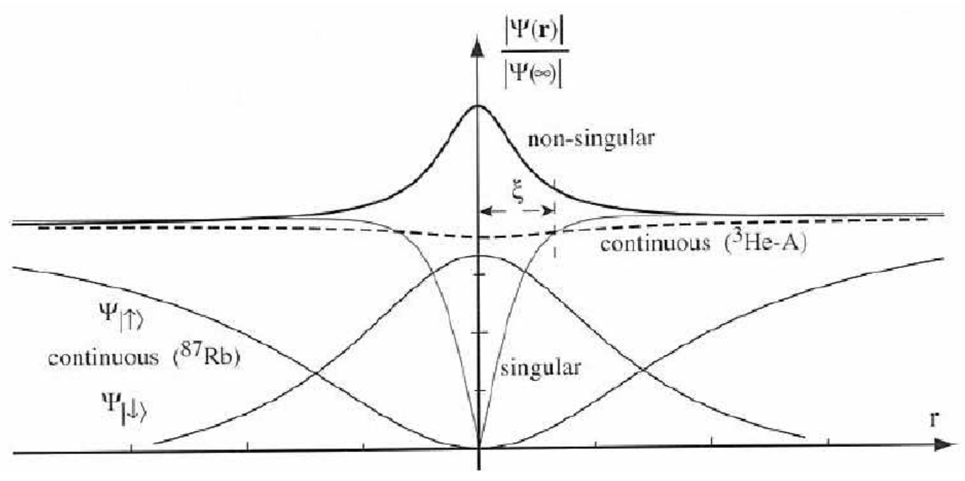
- In 3D exchange of particles produces a trivial phase factor $e^{i2\theta} = 0, \pi$ since the path is deformable to a point.
- Only Bose and Fermi statistics permitted
- In 2D θ is arbitrary - left and right trajectories are not equivalent.



T-L. Ho Phys. Rev. Lett 87, 060403 (2001)

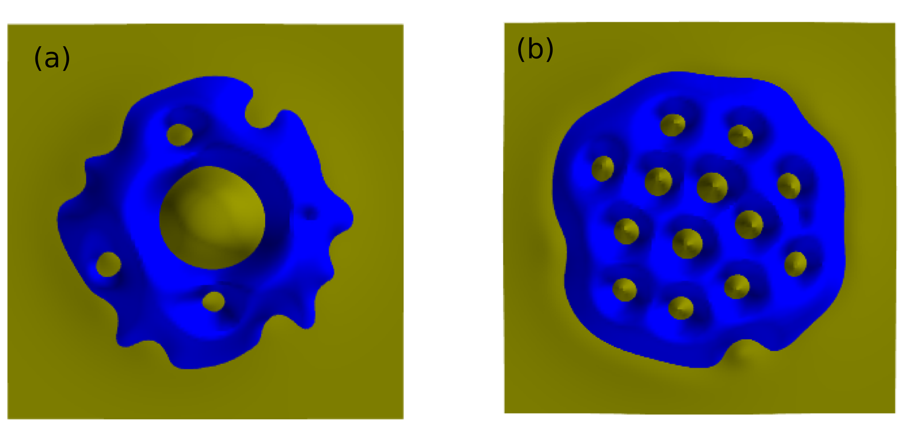
Vortices in a polariton condensate

Multiquantized vortices can be uniquely observed in polariton condensates with a structure stabilized by the dissipative nature



$$E_v \approx l^2 \pi n_C \frac{\hbar^2}{m}\ln\frac{b}{\xi}$$

(a) Polariton condensates can be very dissipative and form stable multiquantized vortices



or (b) they can be pushed into a conservative regime in which an Abrikosov lattice forms

What does a polariton condensate contribute to new states of quantum vortex matter?

Vortices are unique in the polariton condensate than in other quantum liquids
* **Multiquantized vortices** can be stable
* **Abrikosov lattices** can be formed - density and size easily controlled

Creating quatum vortex states of matter with polariton condensates:

BKT superfluid phase:
- First experimental observation of vortex-antivortex pairs
- Possible to study of the onset of BKT phase as vortex number is increased

Fractional quantum Hall phase:
- Strong potential to observe and manipulate anyonic particles
- Adjustable mass and density parameters -> easier to observe
- Current experiments: rotation with an optical vortex

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