Unraveling the hidden link between composite fermions and the exciton condensate

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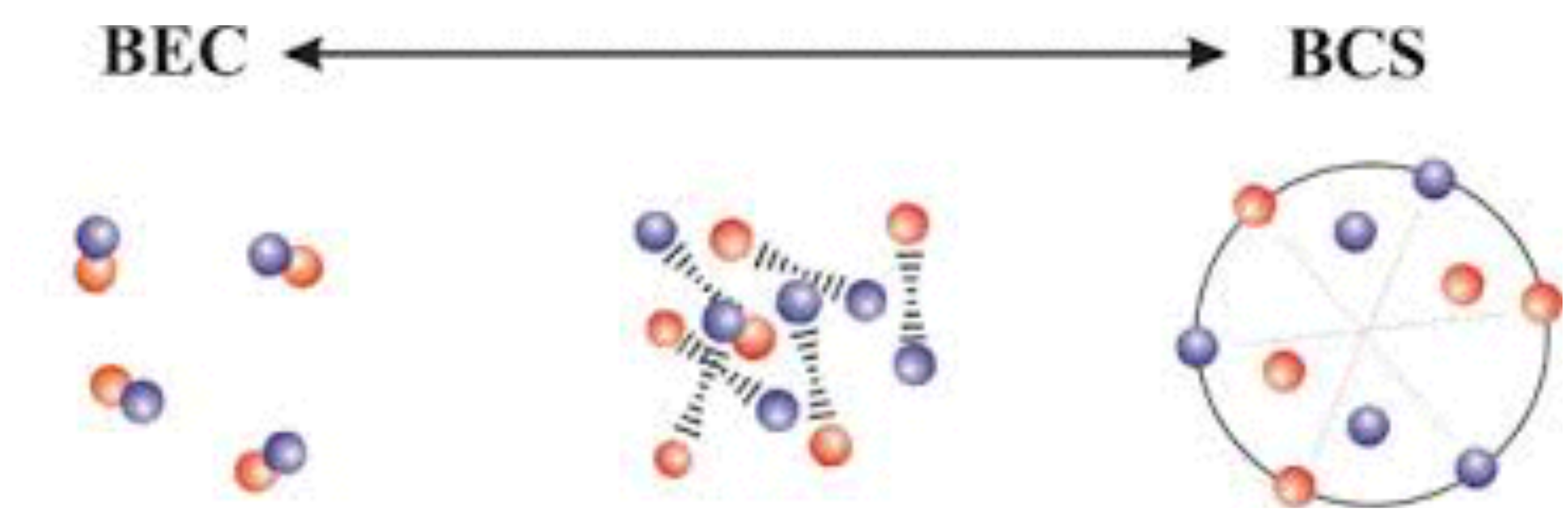
Main message

- The celebrated exciton condensate in quantum Hall bilayers is identical to a BCS-type inter-layer paired state of composite fermions.

I. Sodemann, I. Kimchi (MIT), C. Wang (Harvard), T. Senthil (MIT), Phys. Rev. B **95**, 085135 (2017).

Unification in physics

- Unification is a recurring motif in physics
- BEC - BCS crossover a powerful unification in physics of quantum matter:



s-wave
spin singlet

Bose Einstein condensate molecules

Superconductor Fermions

- Other channels might not have smooth connection:

$p_x + ip_y$
spin polarized

conventional vortices

vortices have majoranas

Unification in condensed matter physics

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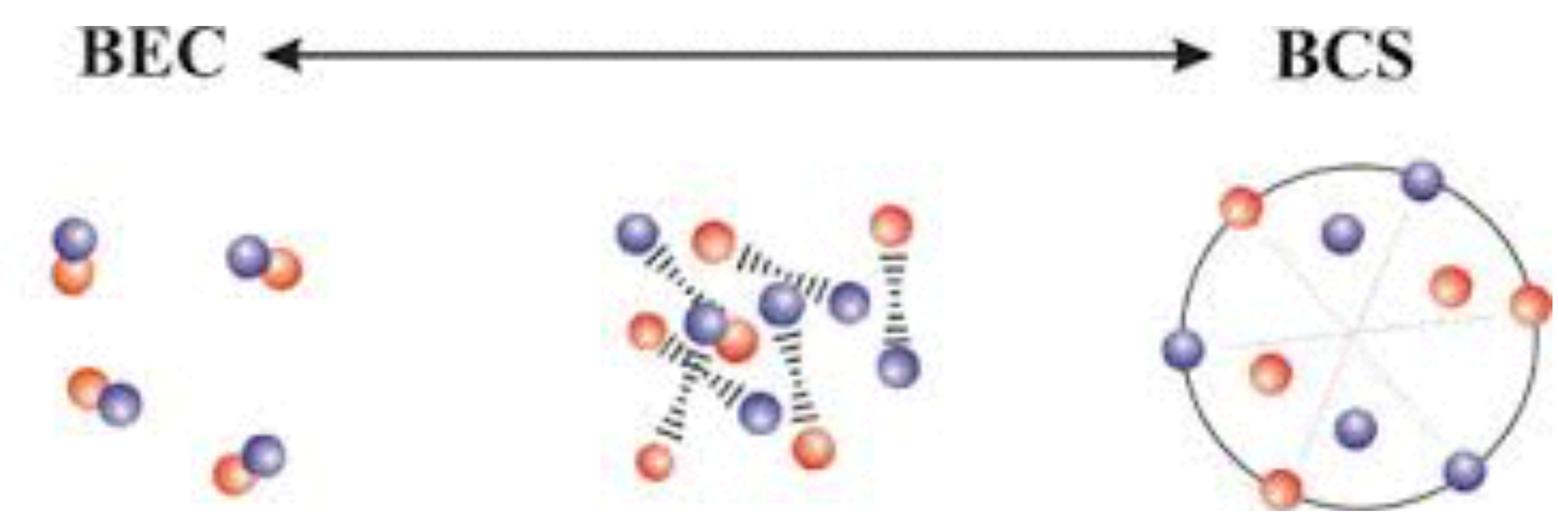
- BEC - BCS crossover a powerful unification in physics of quantum matter:



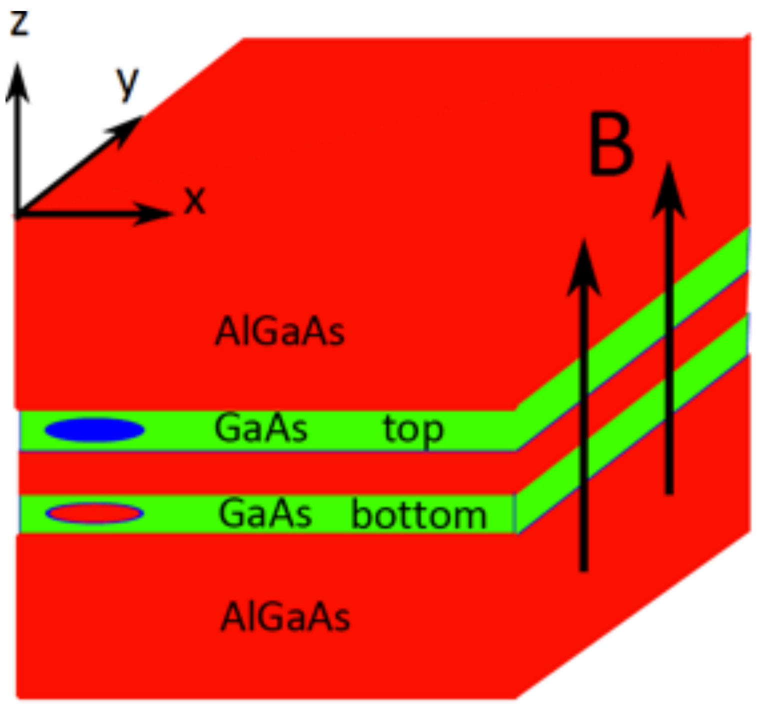
Bose Einstein condensate molecules

Superconductor Fermions

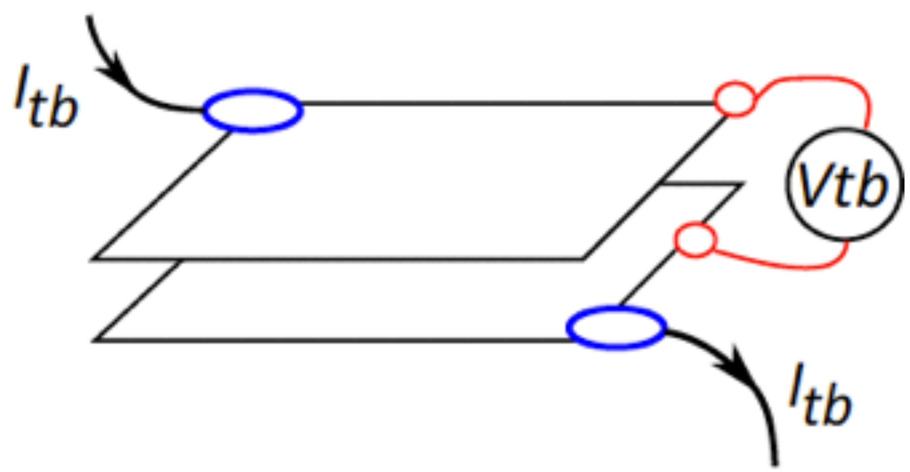
- Unification between two celebrated quantum Hall phases of matter: the **exciton condensate** and the **composite fermion metal.**

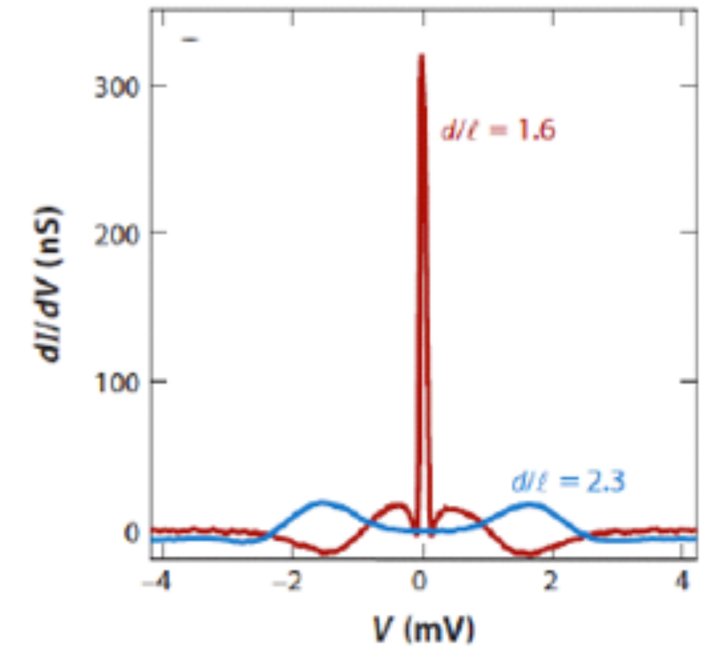
Exciton condensate

- No tunneling but strong interactions

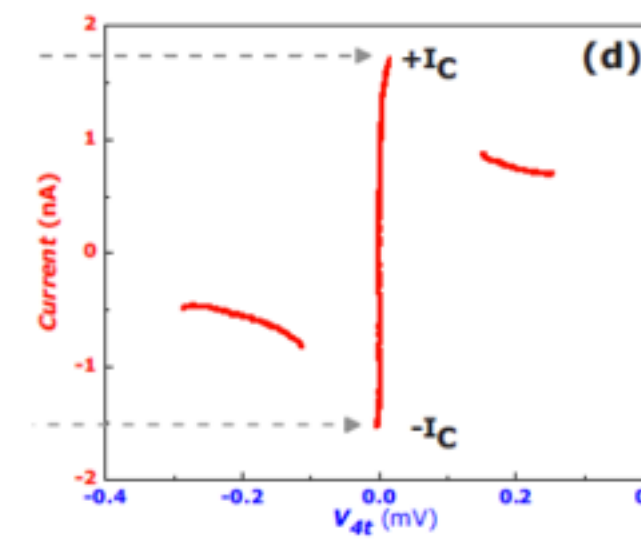


$$\nu = \nu_{top} + \nu_{bottom} = 1/2 + 1/2$$



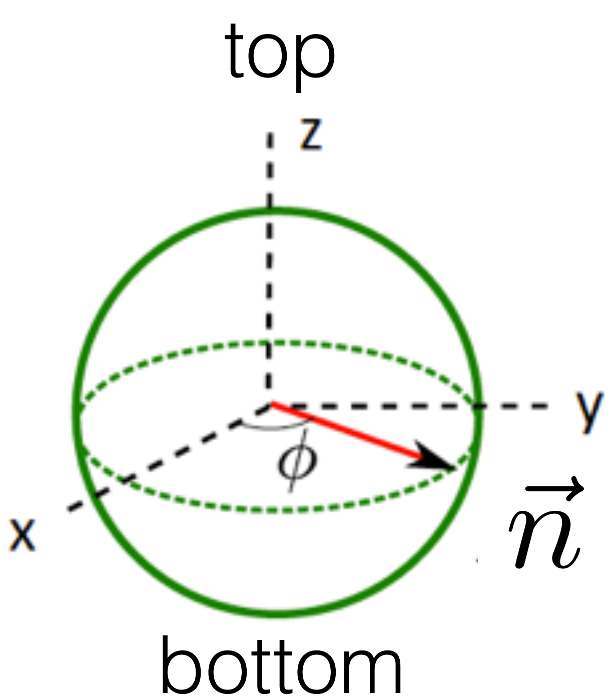


Spielman *et al.*, PRL (2000)



Tiemann *et al.*, PRB (2007)

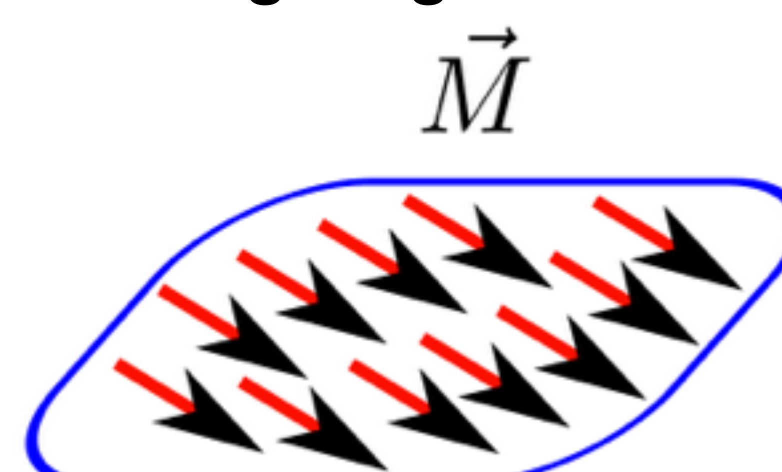
- Exciton condensate:



$$|top\rangle + e^{i\phi}|bottom\rangle$$

$$\langle c^{\dagger}_{\mathrm{bottom}} c_{\mathrm{top}} \rangle \propto e^{i\phi}$$

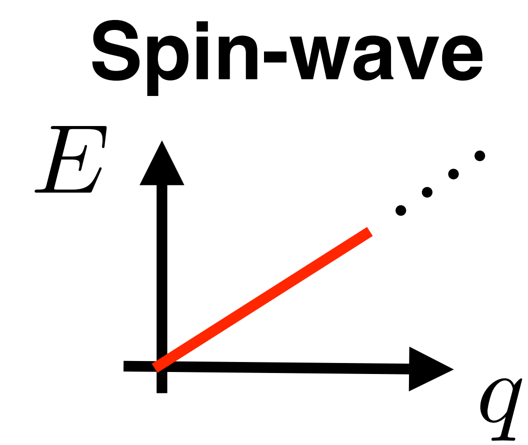
Long range XY order



Properties of exciton condensate

- Superfluidity for charge imbalance:

$$Q_- = Q_{top} - Q_{bottom} \qquad [Q_-, \phi] = i$$



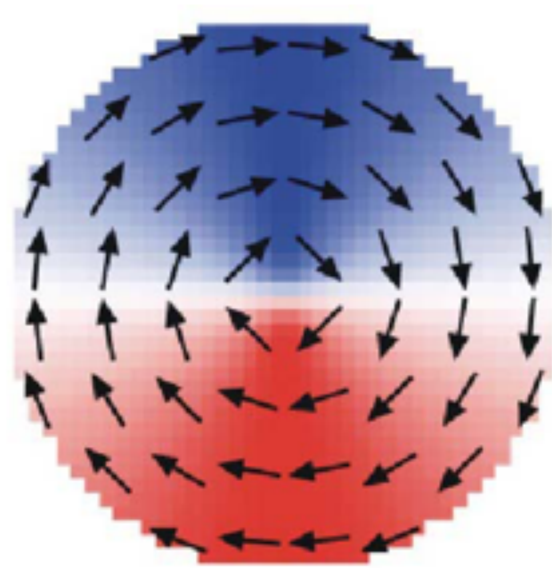
- Linearly dispersing Goldstone mode of ϕ (pseudo-spin wave).

- Half-charged vortices (merons):

2π winding

$v = 1$

$Q_+ = e/2$



$$Q_+ = (v n_z)\,\frac{e}{2}$$

$$v \in \mathbb{Z}$$

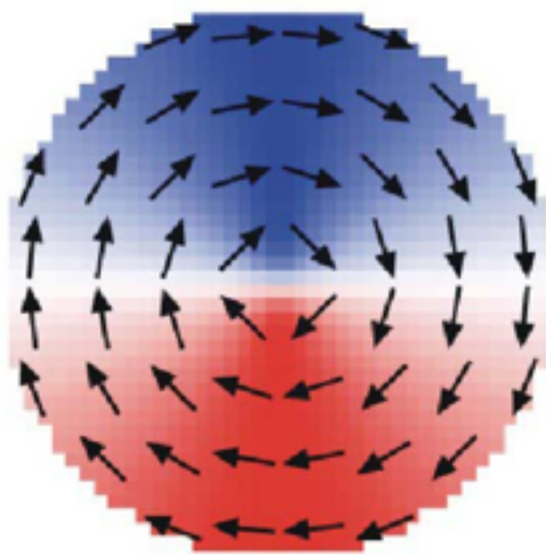
$$n_z = \pm 1$$

- Wen, Zee, PRL 69, 1811 (1992).
- Moon, Mori, Yang, Girvin, MacDonald, Zheng, Yoshioka, Zhang, PRB 51, 5138 (1995).

Properties of exciton condensate

- Half-charged vortices (merons):

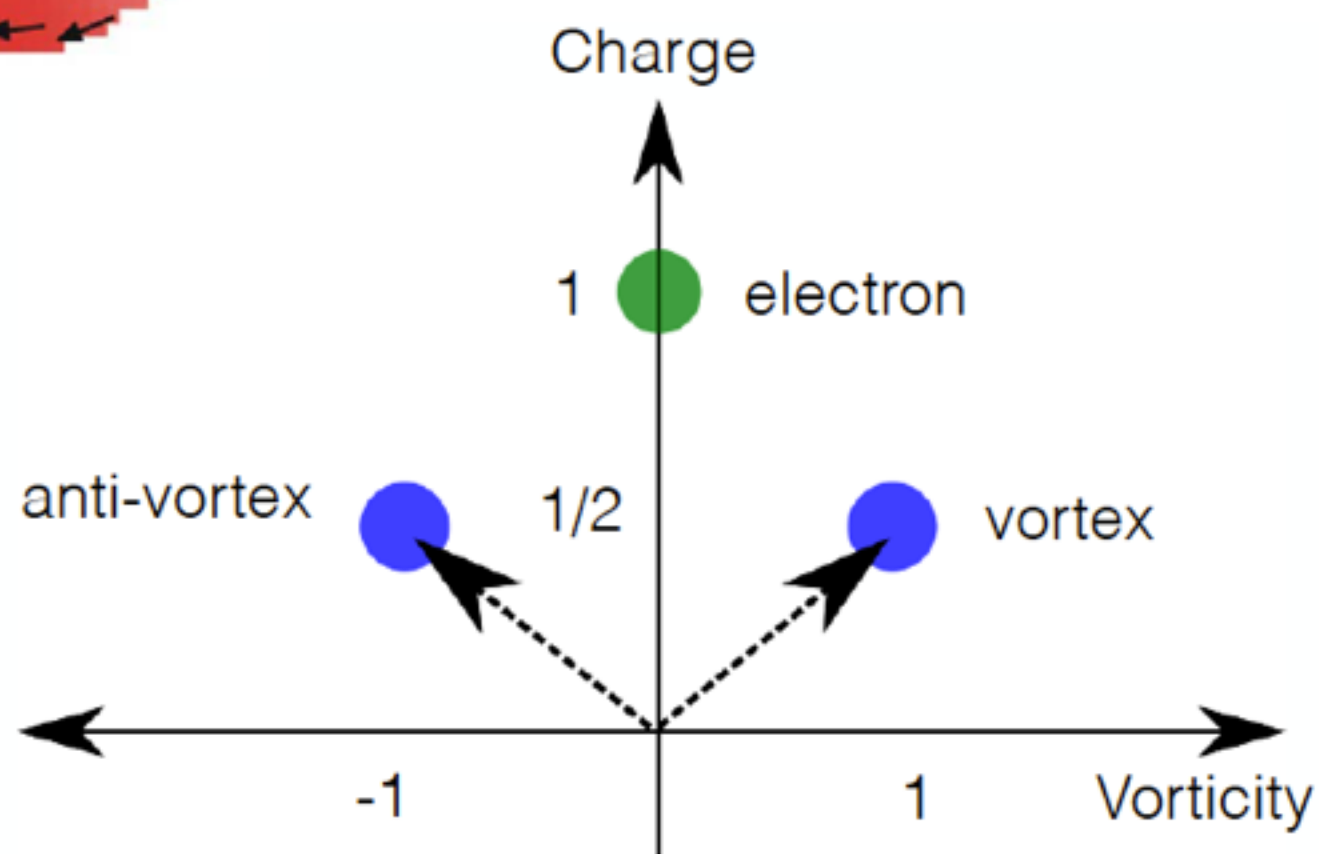
2π winding



$$Q_+ = (v n_z)\ \frac{e}{2}$$

$v = 1$
$Q_+ = e/2$

$v = \pm 1$
$n_z = \pm 1$

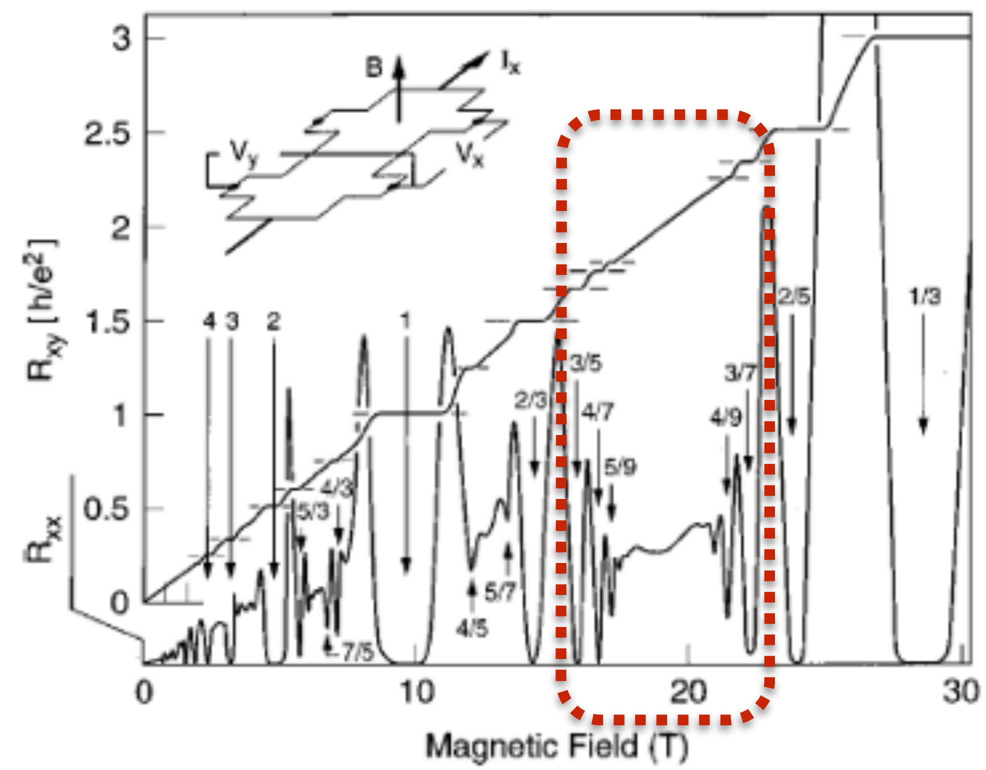


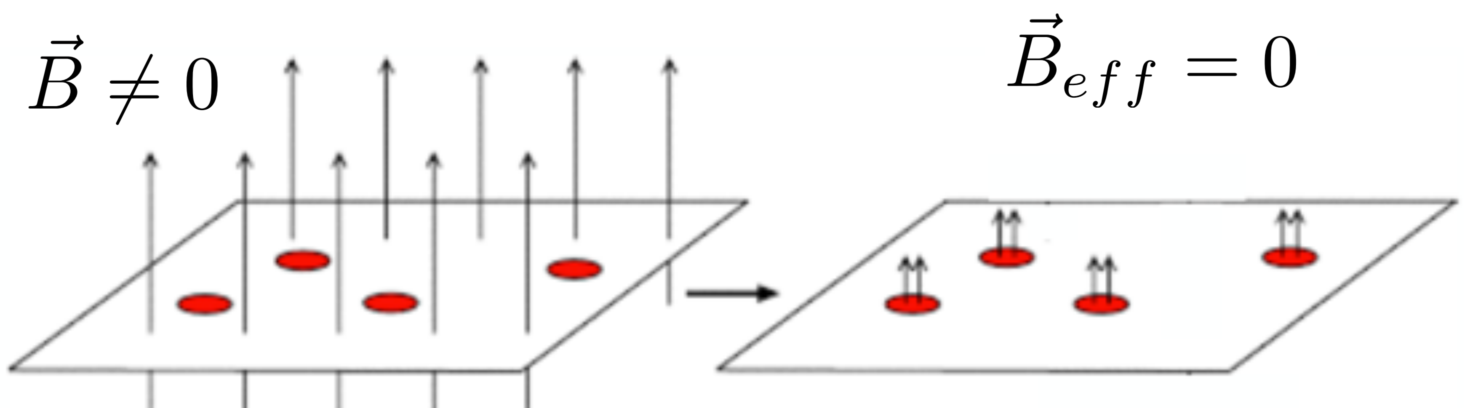
Composite fermion metal

- Fractionalized metal for half filled landau level:

$$N_e = \frac{1}{2} N_\phi$$

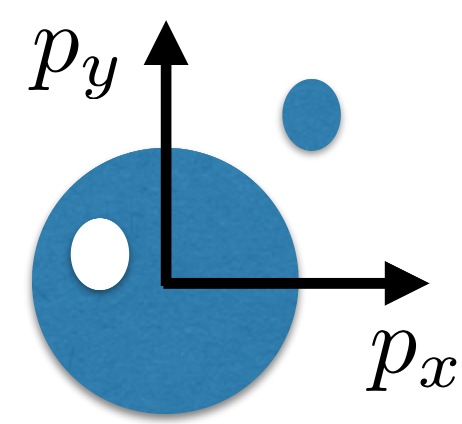
- Composite fermion: electron bound to two vortices





electrons

composite fermions



composite fermion fermi surface

- Emergent 2-dimensional “gauge field” (analogous to the electro-magnetic field in 2D).

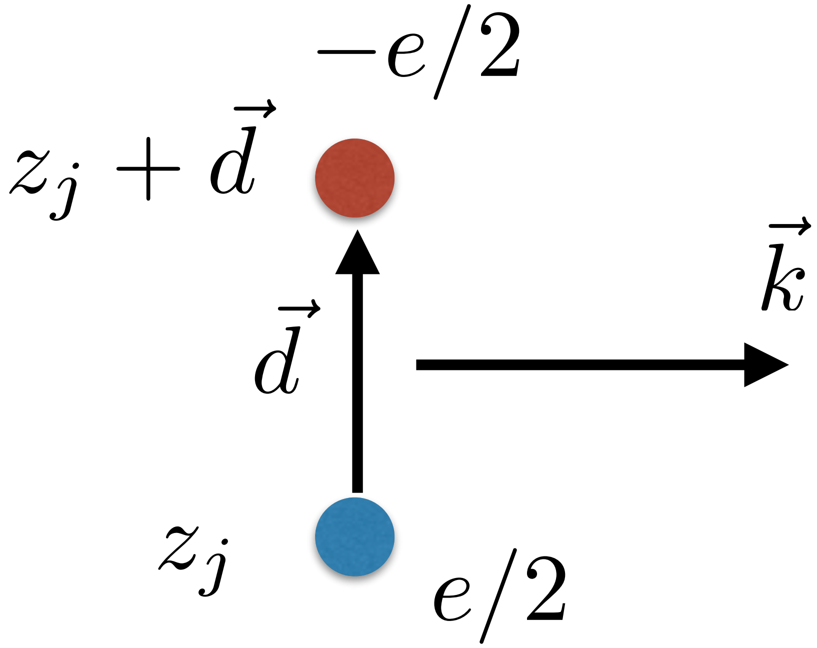
Jain, PRL (1989). Halperin, Lee, Read, PRB (1993).

Anatomy of Composite fermion metal

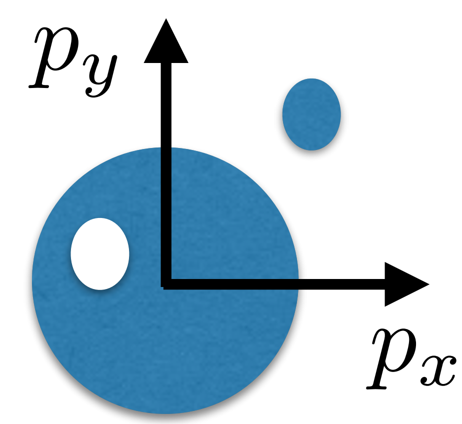
- Composite fermion is a dipolar object electron bound to two vortices:

Bosons: $$\Psi^{1/2}_{Laughlin} \sim \prod_{i<j} (z_i - z_j)^2$$

Fermions: $$\Psi^{1/2}_{CFL} \sim \prod_{i<j} (z_i - z_j)(z_i - d_i - z_j - d_j)$$



$$k_i = l^2 d_i \times \hat{z}$$



composite fermion fermi surface

Read, Sem. Sci. & Tech. (1994).

Wang & Senthil, PRB (2016).

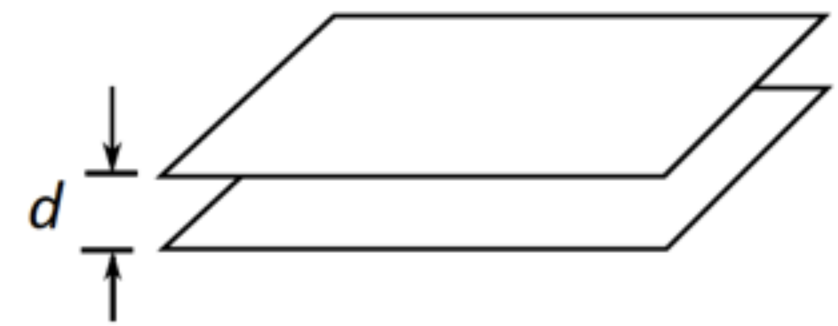
Bilayer exciton condensate and Composite fermion metal

- Are zero and infinite distance connected?

$$\nu = \nu_{top} + \nu_{bottom} = 1/2 + 1/2$$

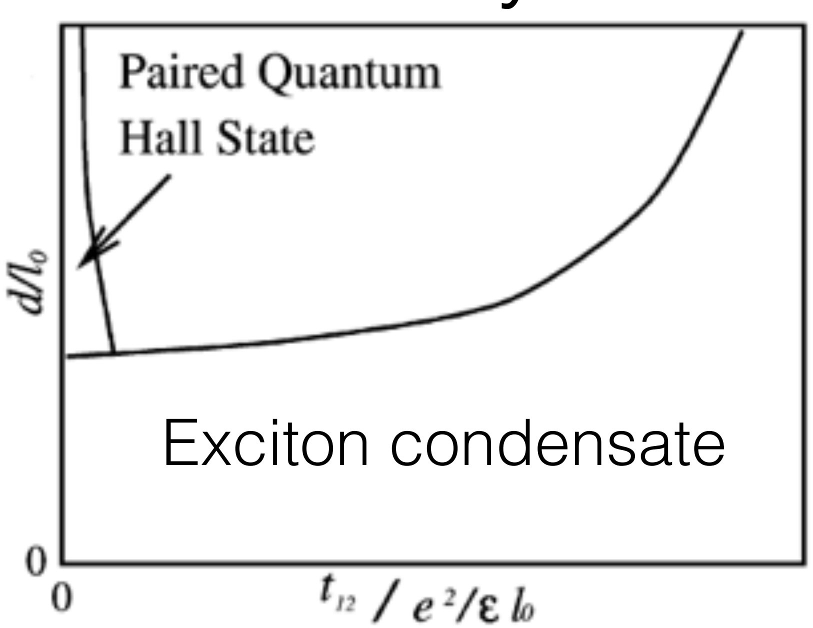
$d = 0$  $d = \infty$

Exciton condensate ? Two C-Fermion metals



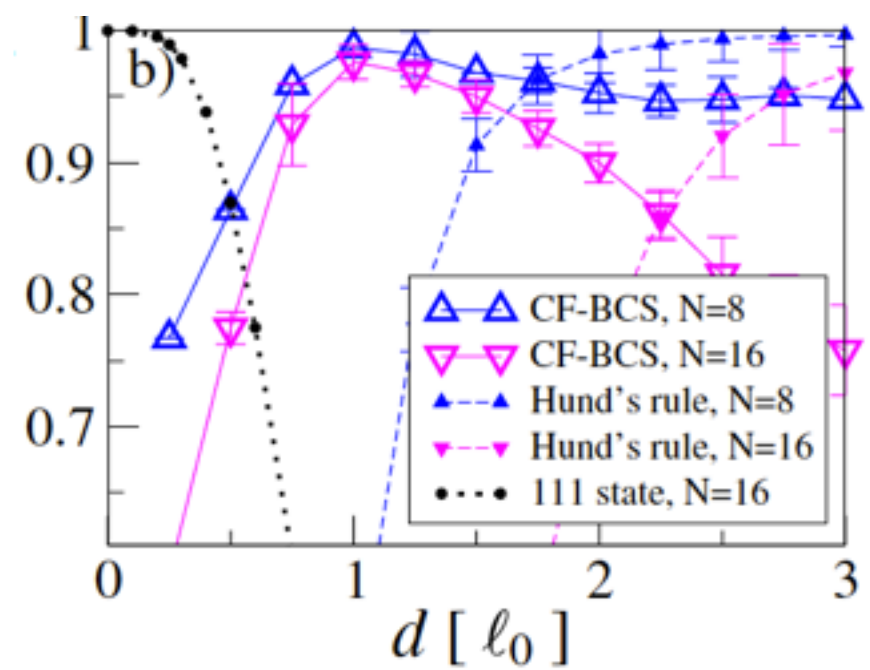
- Precedents

Theory



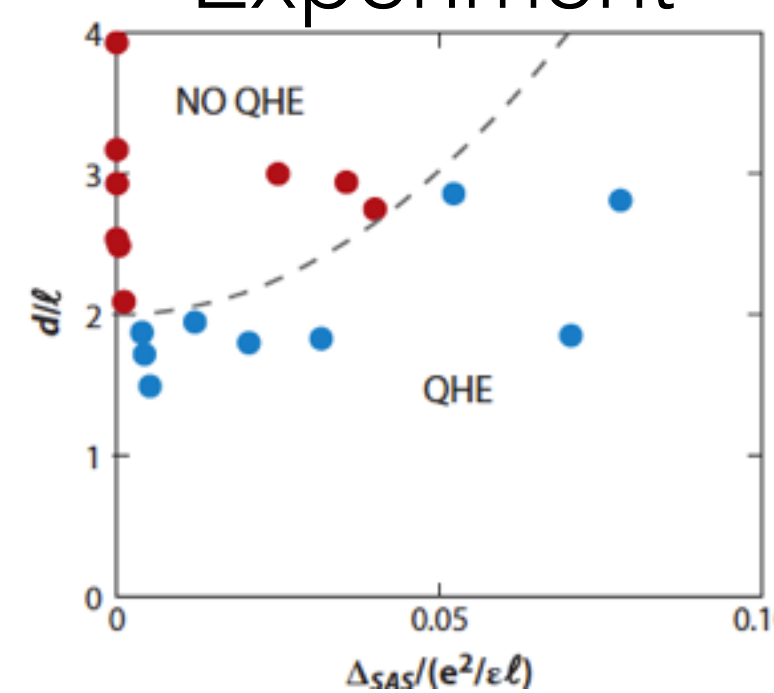
Bonesteel et al. PRL(1996)

Numerics



Möller et al. PRL (2008)

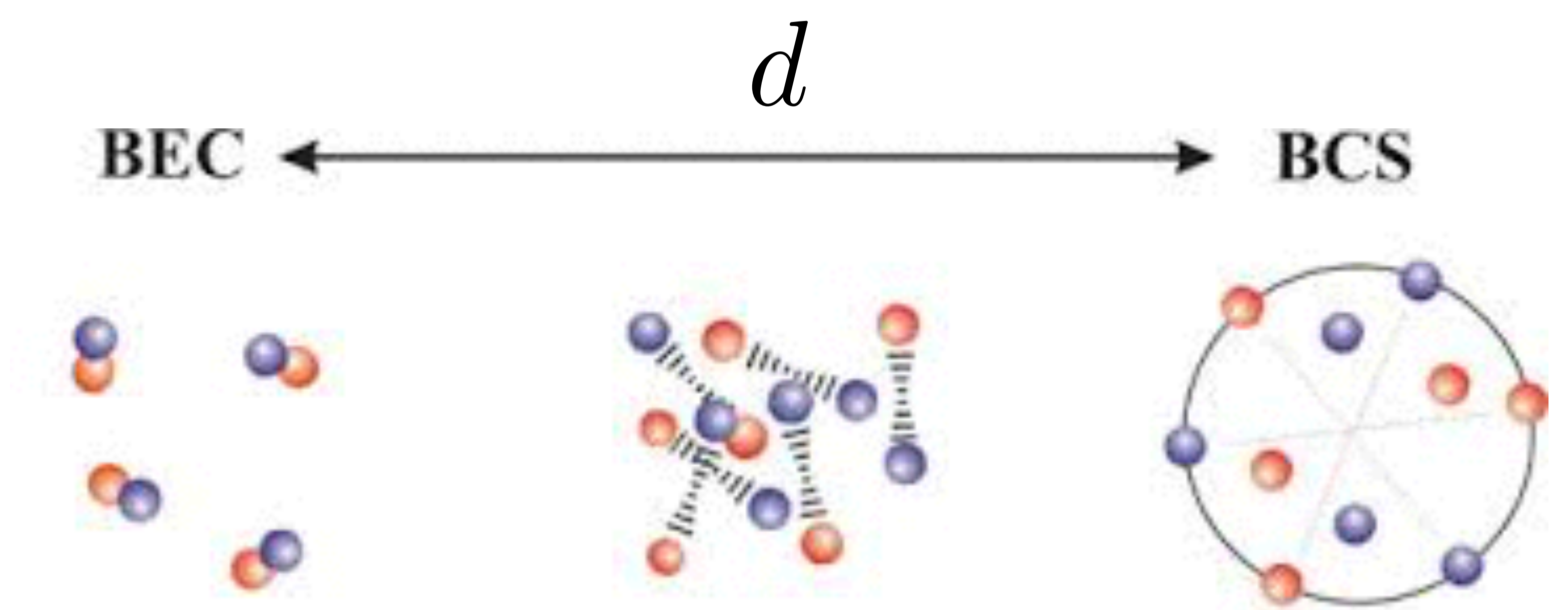
Experiment



Eisenstein, ARCMP (2014)

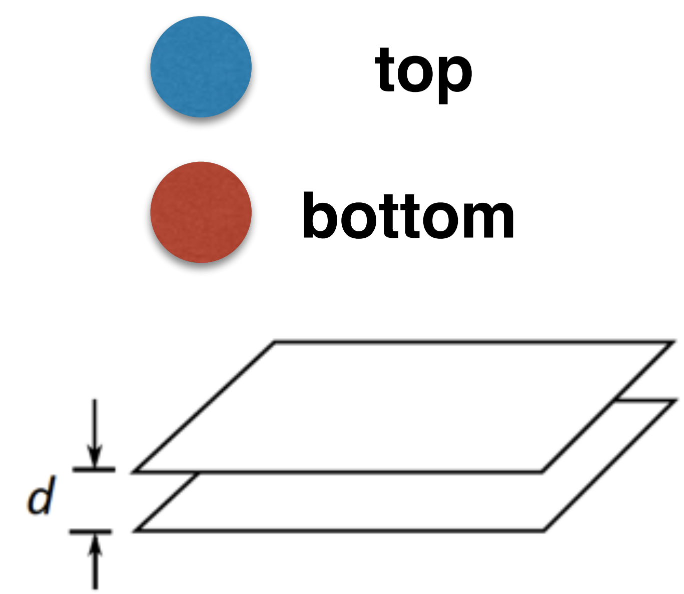
Bilayer exciton condensate and Composite fermion metal

- A special particle-hole invariant “cooper pairing” of composite fermions is equivalent to exciton condensate:



Exciton condensate

Composite fermion Cooper pairs

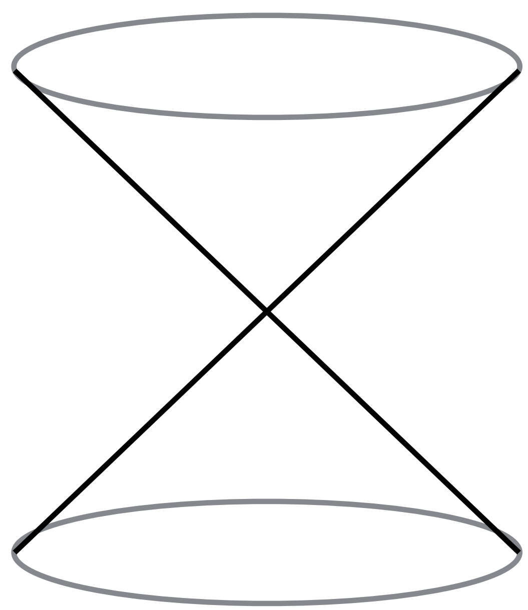


$$\hat{\Delta} = i\psi^\dagger \sigma_y \tau_x \psi^\dagger \sim i\psi^\dagger_{\mathrm{top}} \sigma_y \psi^\dagger_{\mathrm{bottom}}$$

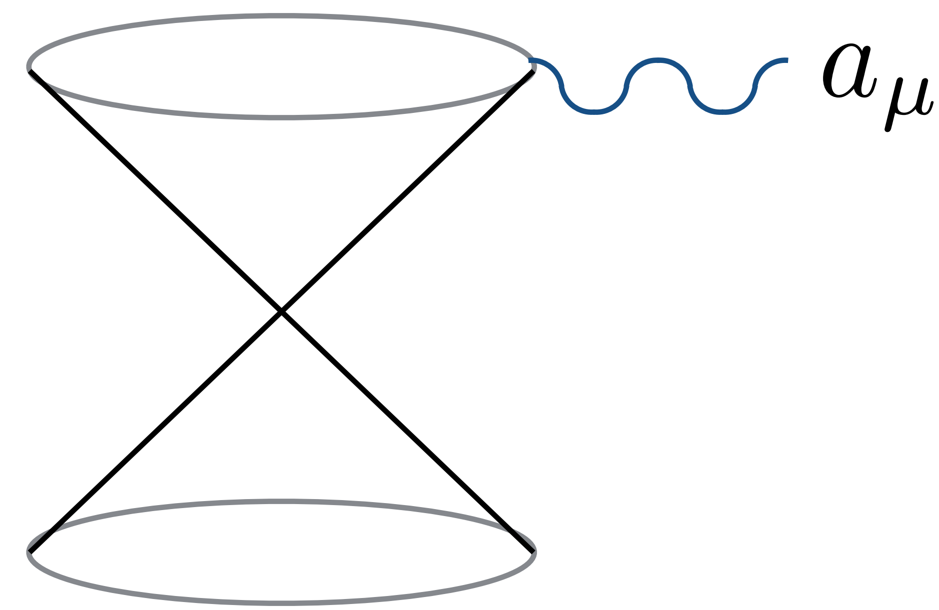
I. Sodemann, I. Kimchi, C. Wang, T. Senthil, Phys. Rev. B **95**, 085135 (2017).

Fermion vortex duality

Physical
Dirac fermion



Dirac composite
fermion vortex



$$\mathcal{L}_e = \bar{\psi}_e(i\not{\partial} - \not{A})\psi_e + \mathcal{L}_{\text{int}}$$

$$\delta n_{elec}(r) = \frac{\nabla \times \vec{a}}{4\pi}$$

$$\psi_e^\dagger \leftrightarrow M_{4\pi}$$

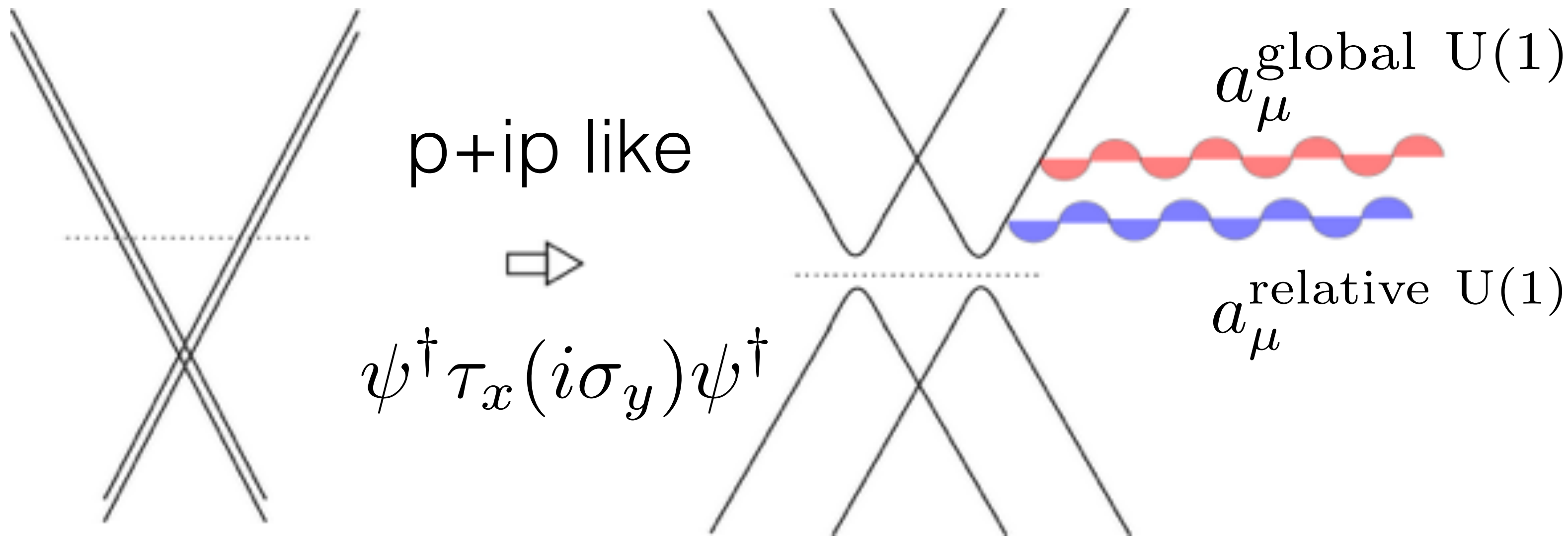
$$\mathcal{L}_{cf} = \bar{\psi}_{cf}(i\not{\partial} - \not{a})\psi_{cf} + \frac{adA}{4\pi} + \mathcal{L}_{\text{int}}$$

$$\hat{z} \times \vec{j}_{elec}(r) = \frac{\nabla a_0 + \partial_t \vec{a}}{4\pi}$$

Electron creation is flux
insertion operator

Son PRX (2015). Wang, Senthil PRB (2016). Metlitski, Vishwanath, PRB (2015). Mross, Alicea, Motrunich PRL (2016). Seiberg, Wang, Senthil, Witten Ann. Phys. (2016).

Exciton condensate from CF pairing



$$a_+ = \frac{a_1 + a_2}{2}$$

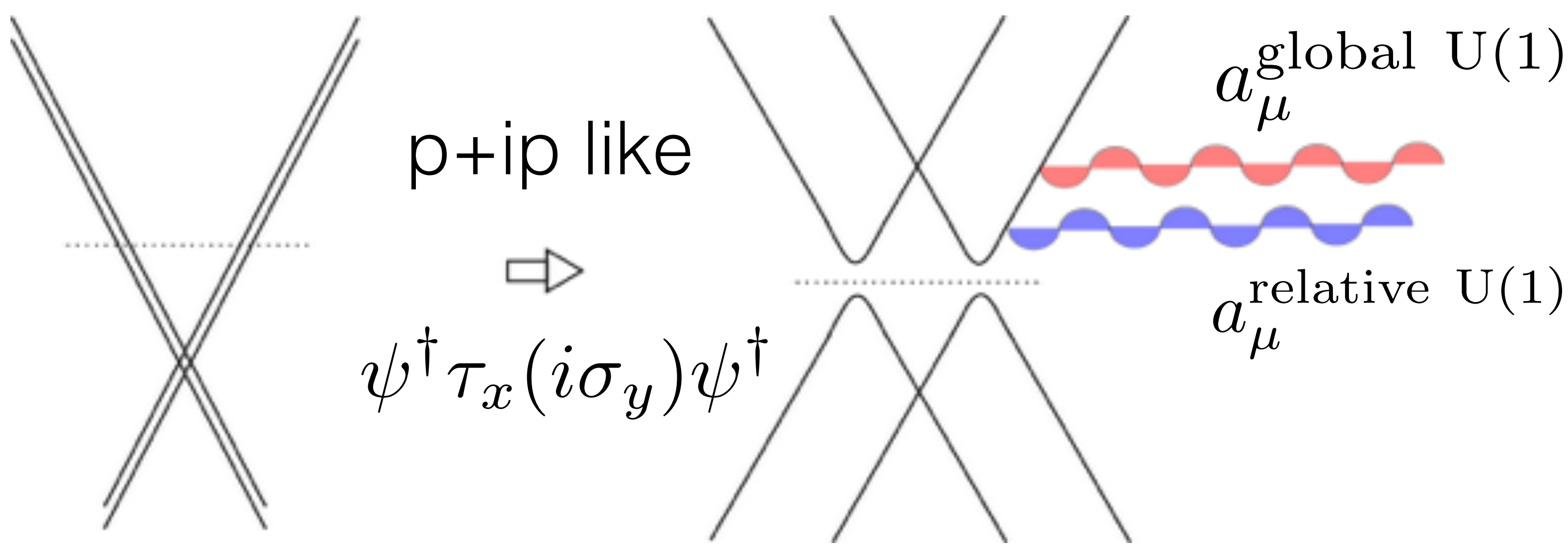
$$a_- = \frac{a_1 - a_2}{2}$$

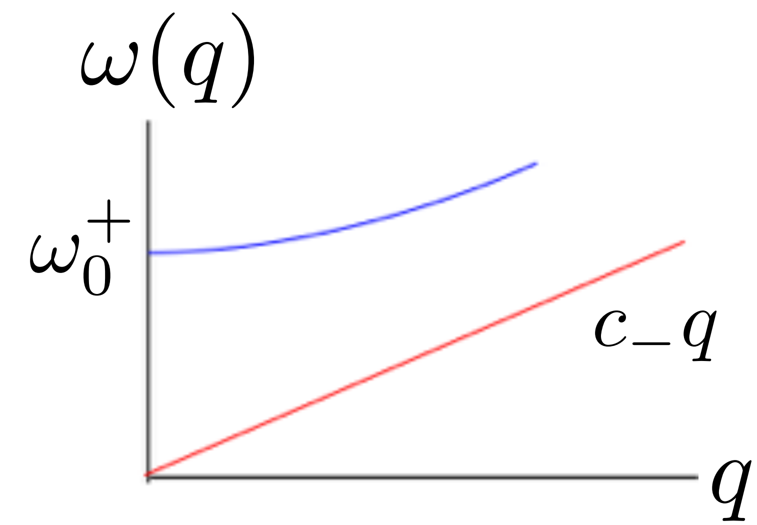
- Symmetric gauge field is gapped via Higgs.
- Anti-symmetric gauge field remains gapless. 2+1 Maxwell theory has a spontaneously broken symmetry:

$$\langle \mathcal{M}_-(r) \mathcal{M}_-^\dagger(0) \rangle \xrightarrow{|r| \to \infty} \text{const} \qquad n^e_{\text{top}} - n^e_{\text{bottom}} = \frac{\nabla \times \vec{a}_-}{2\pi}$$

$\Rightarrow$ $\langle c^\dagger_{\text{bottom}} c_{\text{top}} \rangle \propto e^{i\phi}$ The state is an exciton condensate!

Relative u(1) photon = Goldstone mode





- Photon is exciton condensate “spin-wave”.
- Electric charges under field a_- are vortices of condensate order parameter:

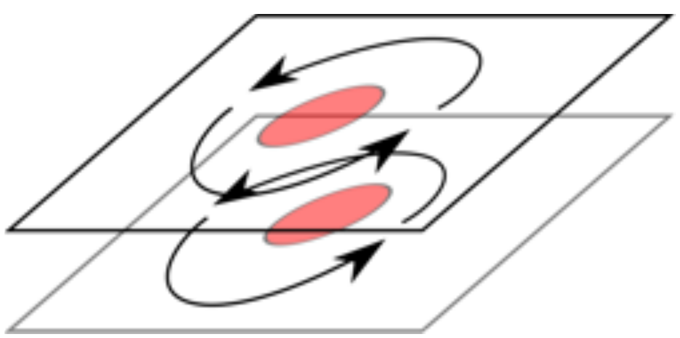
$$4\pi q_- \leftrightarrow vorticity$$

$$\hat{z} \times (\vec{j}_{\text{top}}(r) - \vec{j}_{\text{bottom}}(r)) = \frac{\nabla a_0 + \partial_t \vec{a}}{4\pi}$$

Abrikosov vortices = merons

- Abrikosov vortices carry half charge:

$\pi - \text{vortex}$



$Q = 1/2$

$$n^e_{\text{top}} + n^e_{\text{bottom}} = \frac{\nabla \times \vec{a}_+}{2\pi} \quad \Rightarrow \quad Q_\pi = \pm \frac{1}{2}$$

- Abrikosov vortices have a complex fermion zero mode:

Layer X-change

$|0\rangle \longrightarrow |1\rangle$

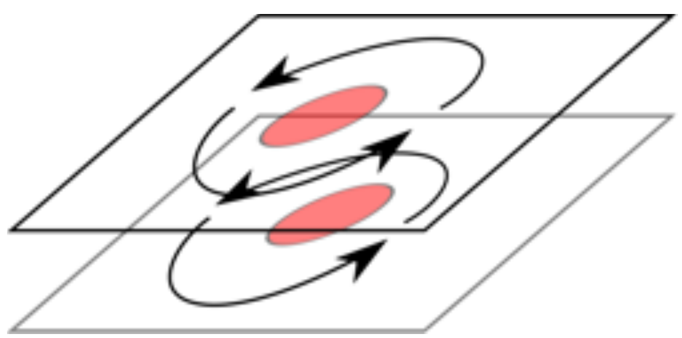
$|1\rangle \equiv \psi_0^\dagger |0\rangle \longrightarrow |0\rangle$

	q_-	(vorticity)
$\|0\rangle$	$1/2$	2π
$\|1\rangle$	$-1/2$	-2π

Abrikosov vortices = merons

- Two π Abrikosov vortices of opposite vorticity are mutual semions

$\pi - \text{vortex}$



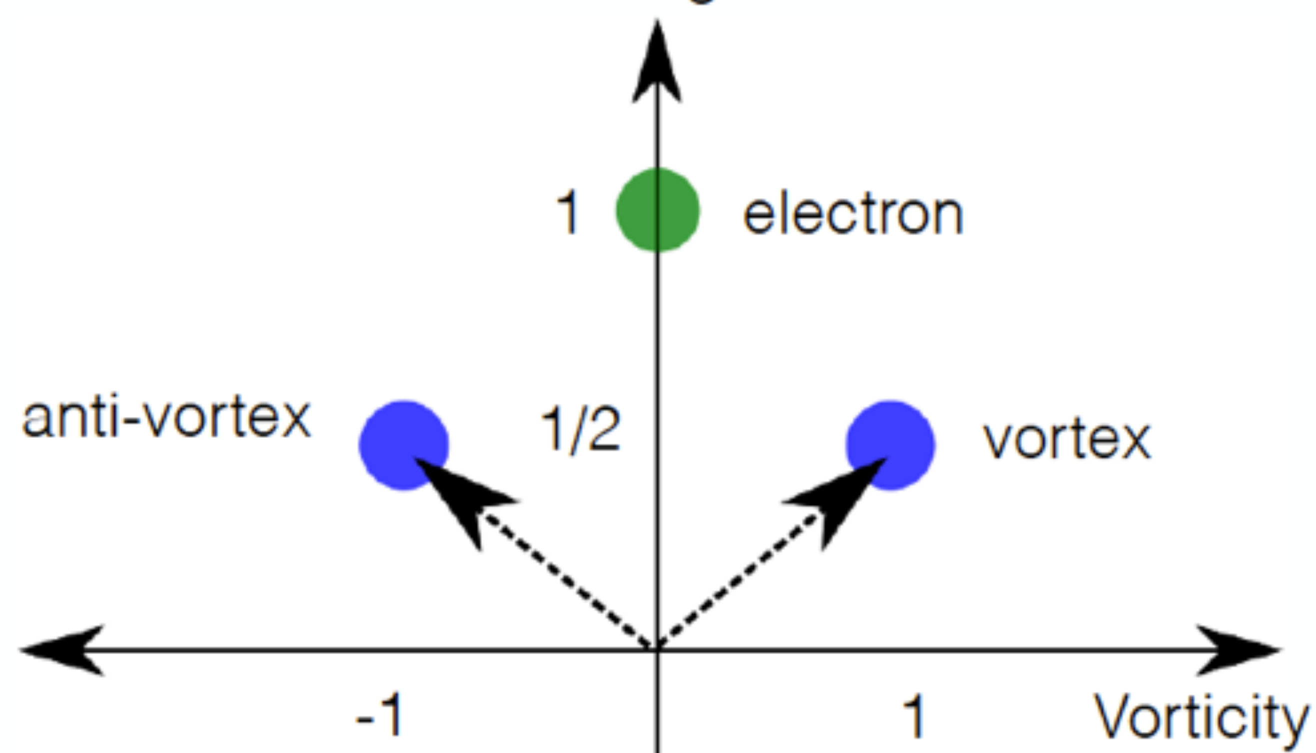
$Q = 1/2$

$$|0\rangle$$

$$|1\rangle \equiv \psi_0^\dagger |0\rangle$$

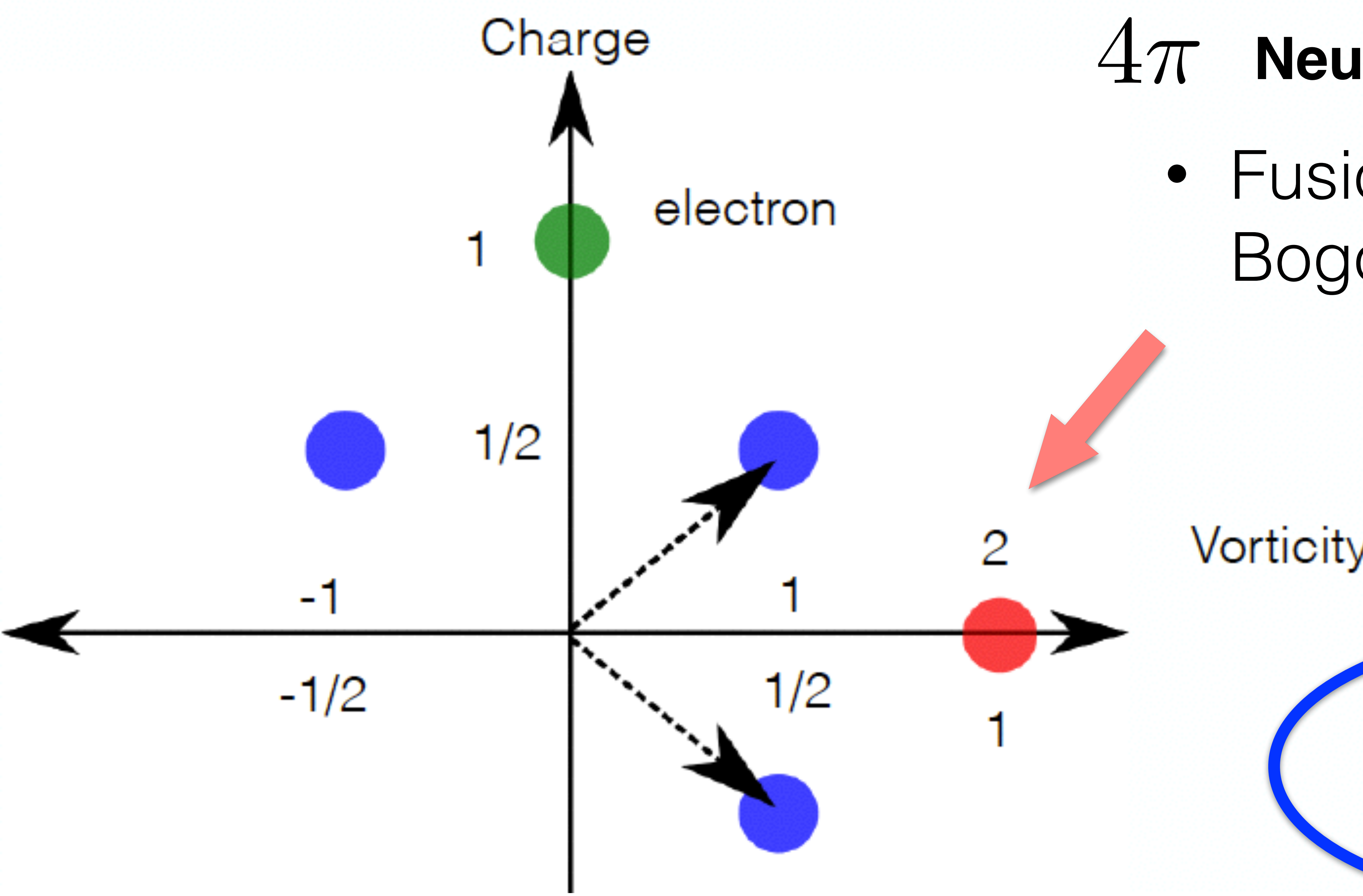
- Their fusion is a fermion:

The electron (with layer charge imbalance neutralized by condensate).



Bogoliubov fermion

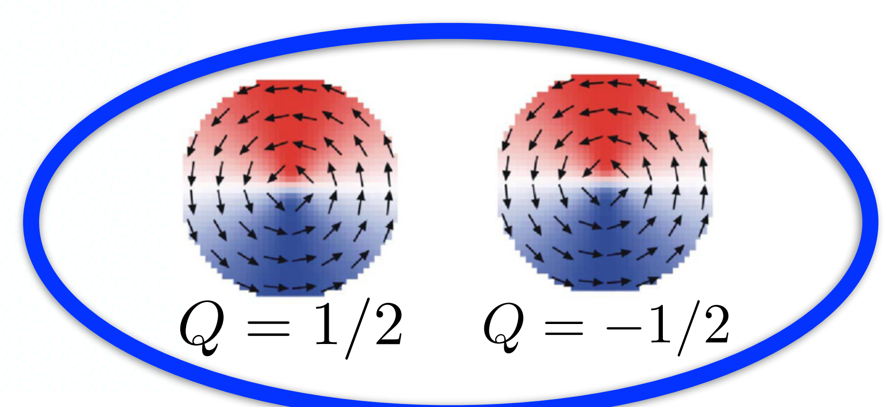
- Consider fusing two Abrikosov vortices of opposite flux but same a_- charge (order parameter vorticity):



4π **Neutral Vortex**

- Fusion is Bogoliubov fermion

4π



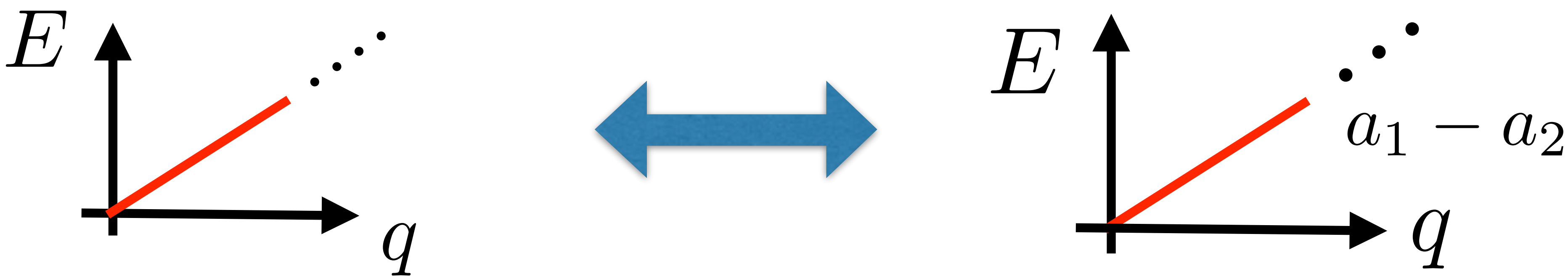
Dictionary

Exciton condensate

Composite fermion superconductor

Spin-wave

Photon



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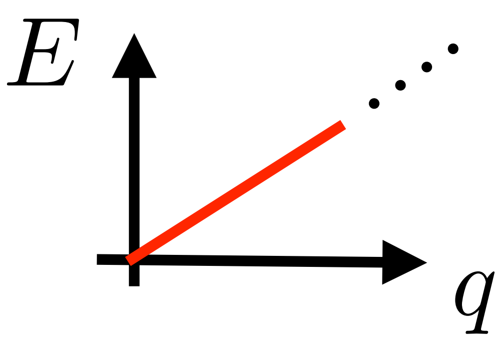
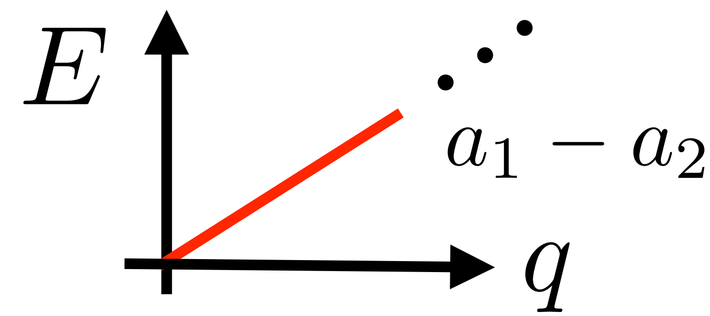


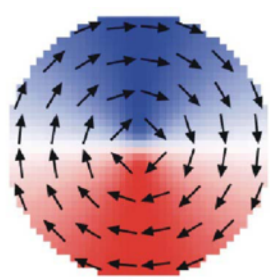
Photon



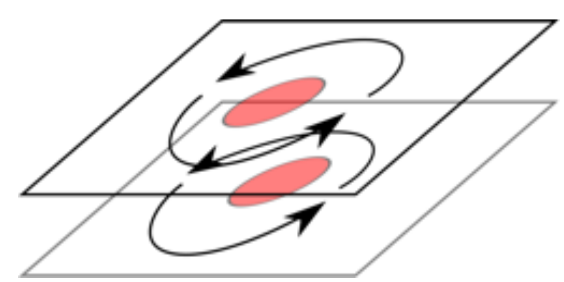
XY vortex

$Q = 1/2$

2π winding



Abrikosov vortex



π flux

$Q = 1/2$

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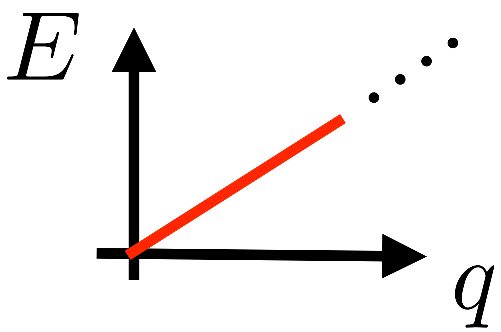
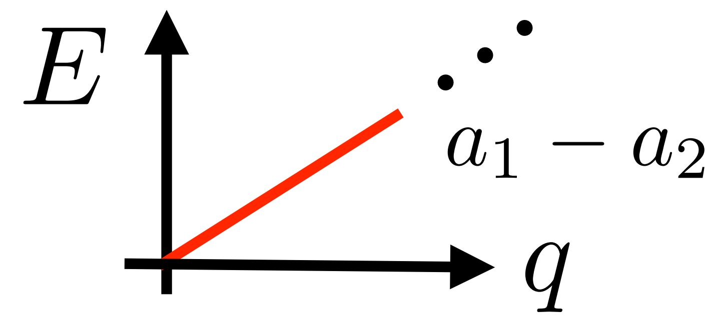


Photon



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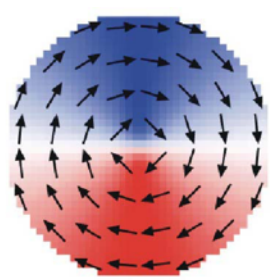
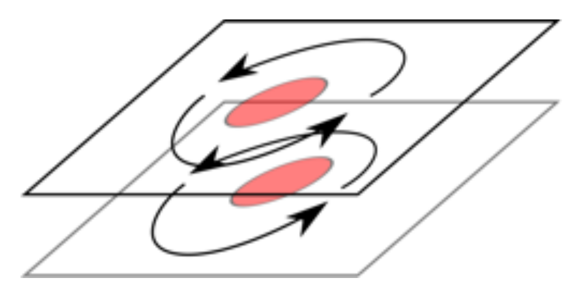


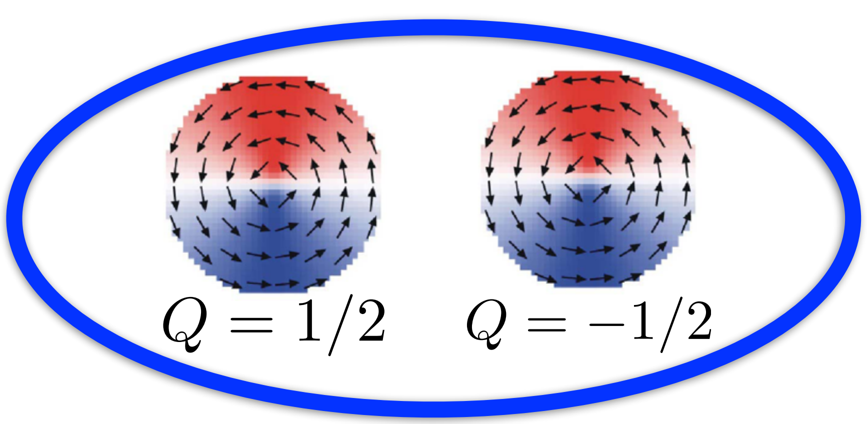
Abrikosov vortex



π flux

$Q = 1/2$

4π **neutral vortex**

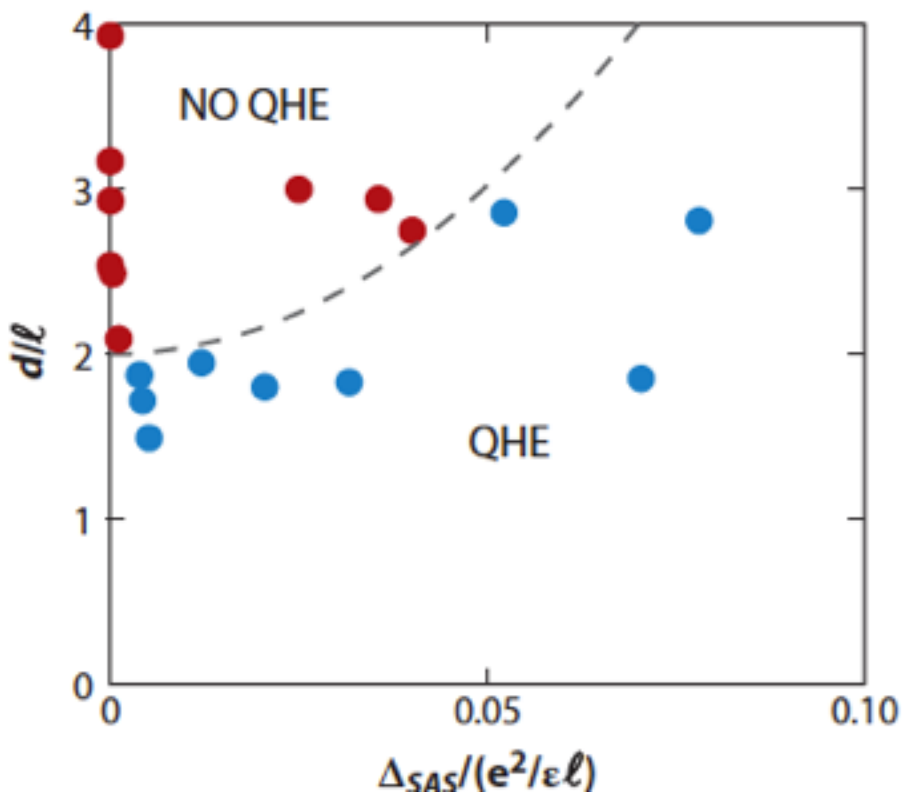


Composite fermion

Charge neutral

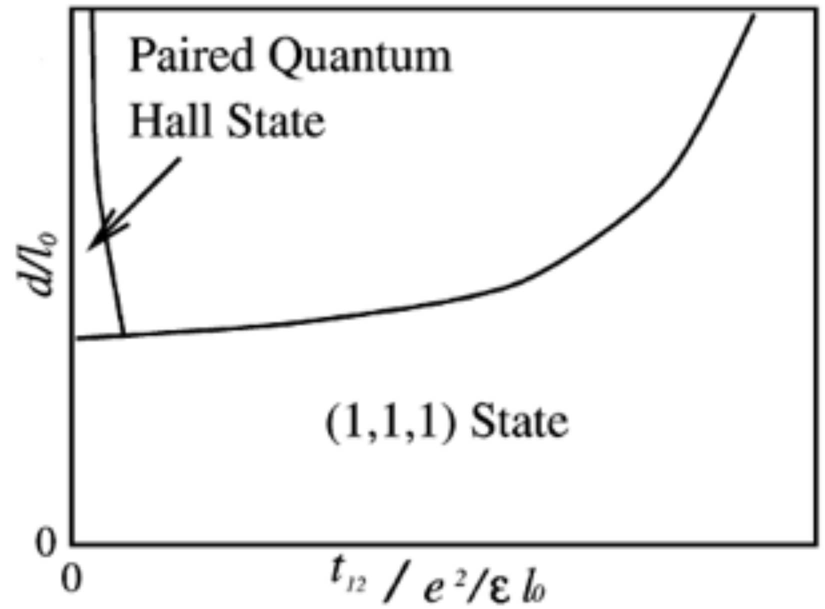
Dipole carrying

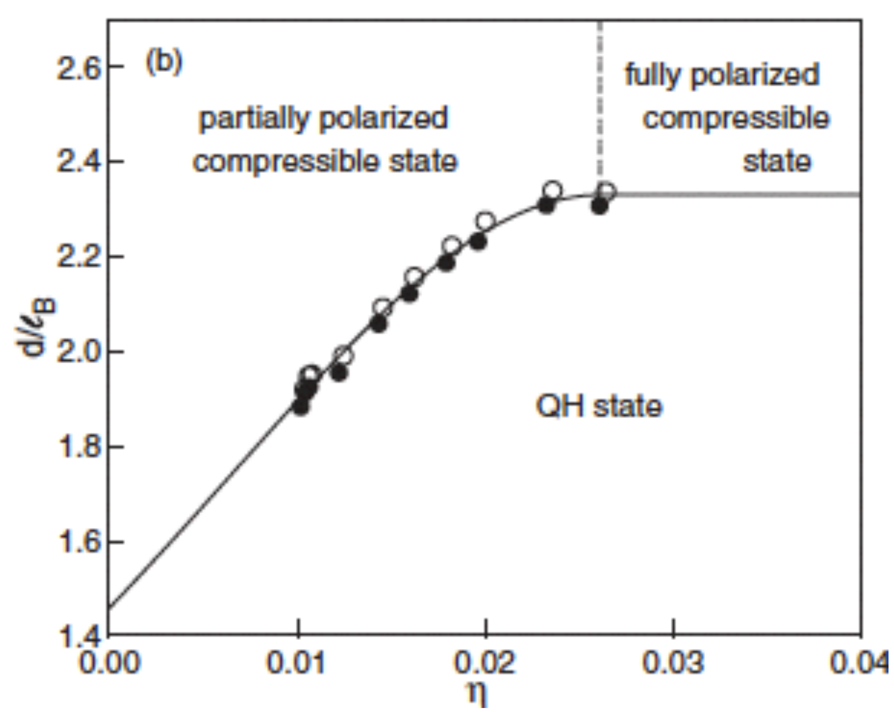
Experiments



Eisenstein, **ARCMP** (2014)

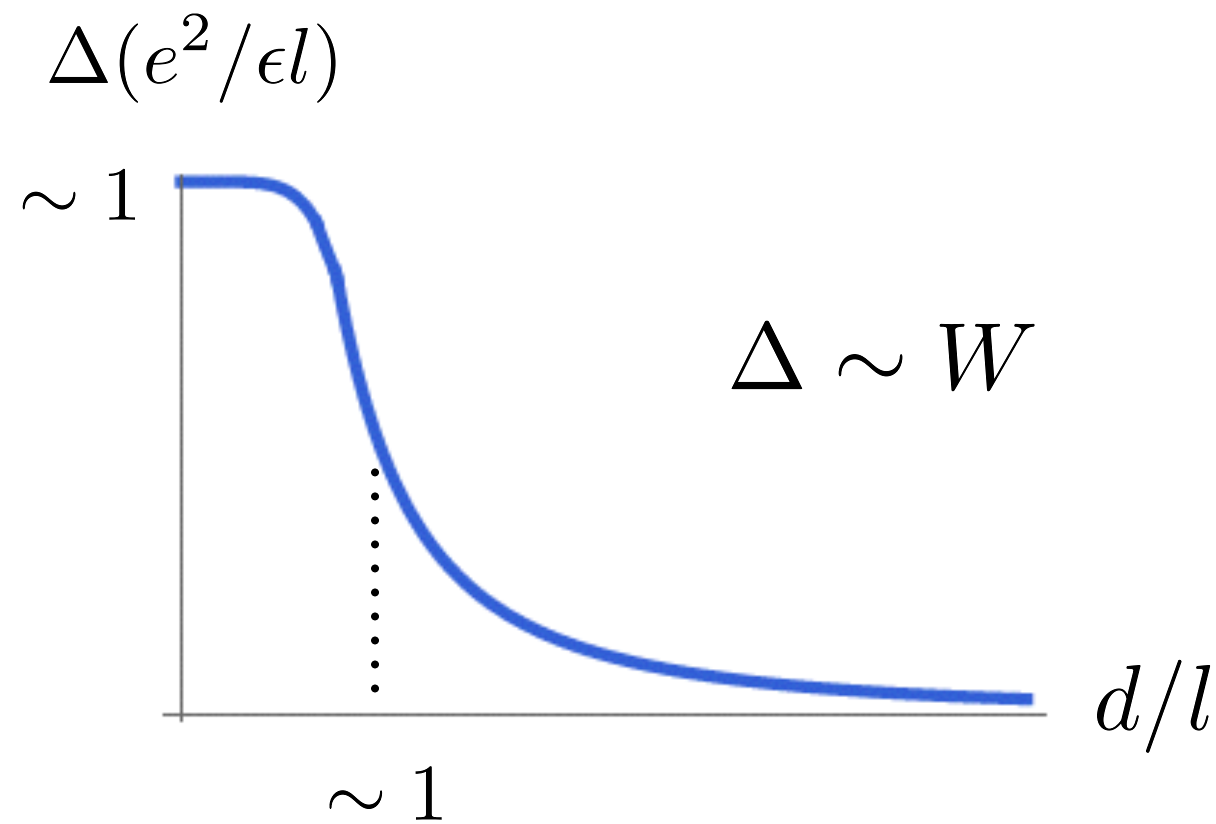
Consider this:
Bonesteel et al. **PRL** (1996)



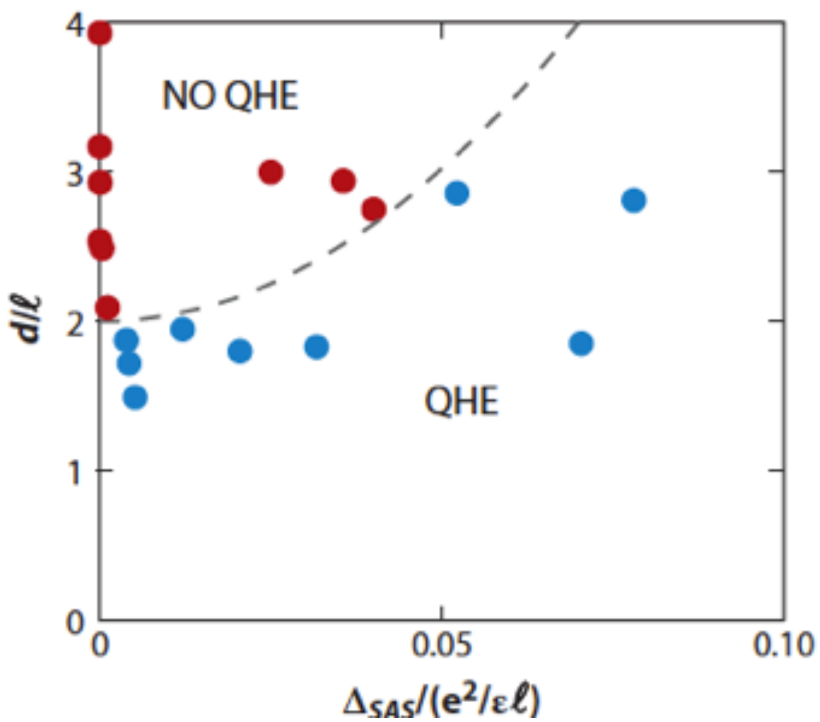


P. Giudici, et al. **PRL** (2008)

Experimental phase transition could be disorder driven:



Experimental tests:



Eisenstein, ARCMP (2014)

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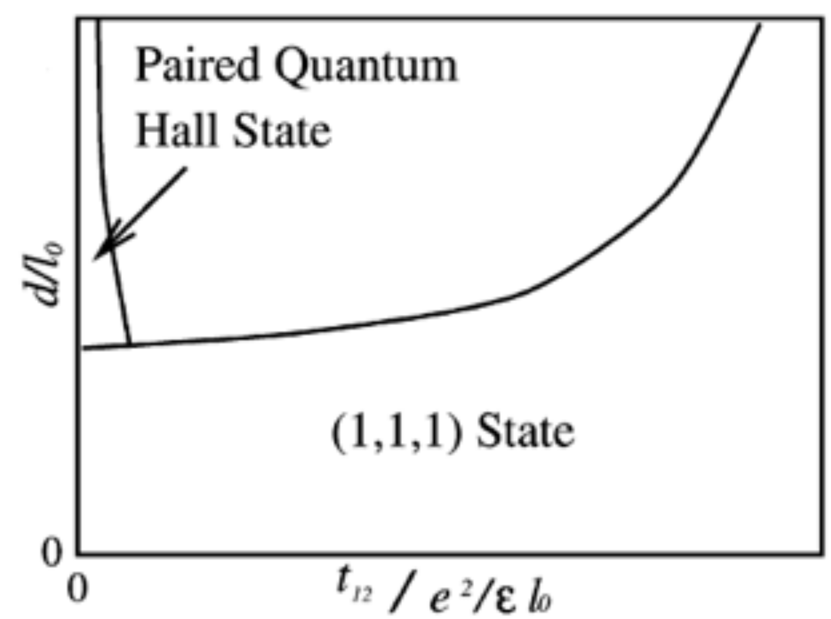
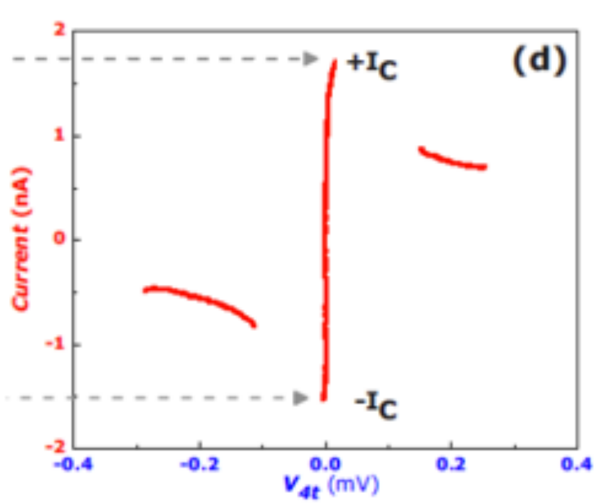
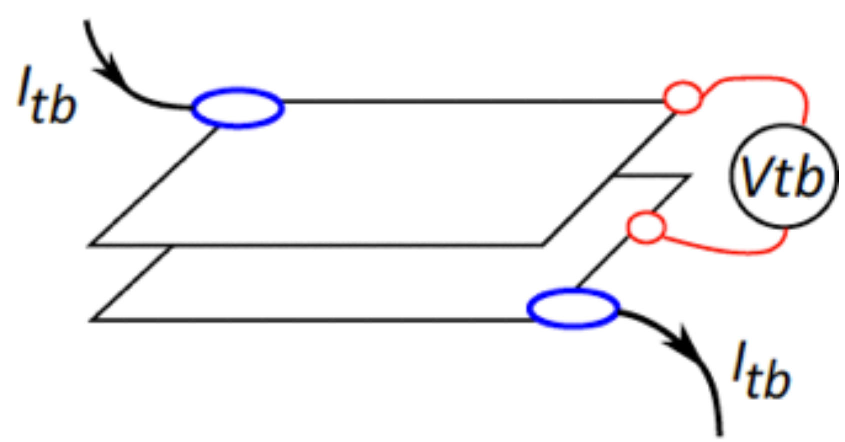
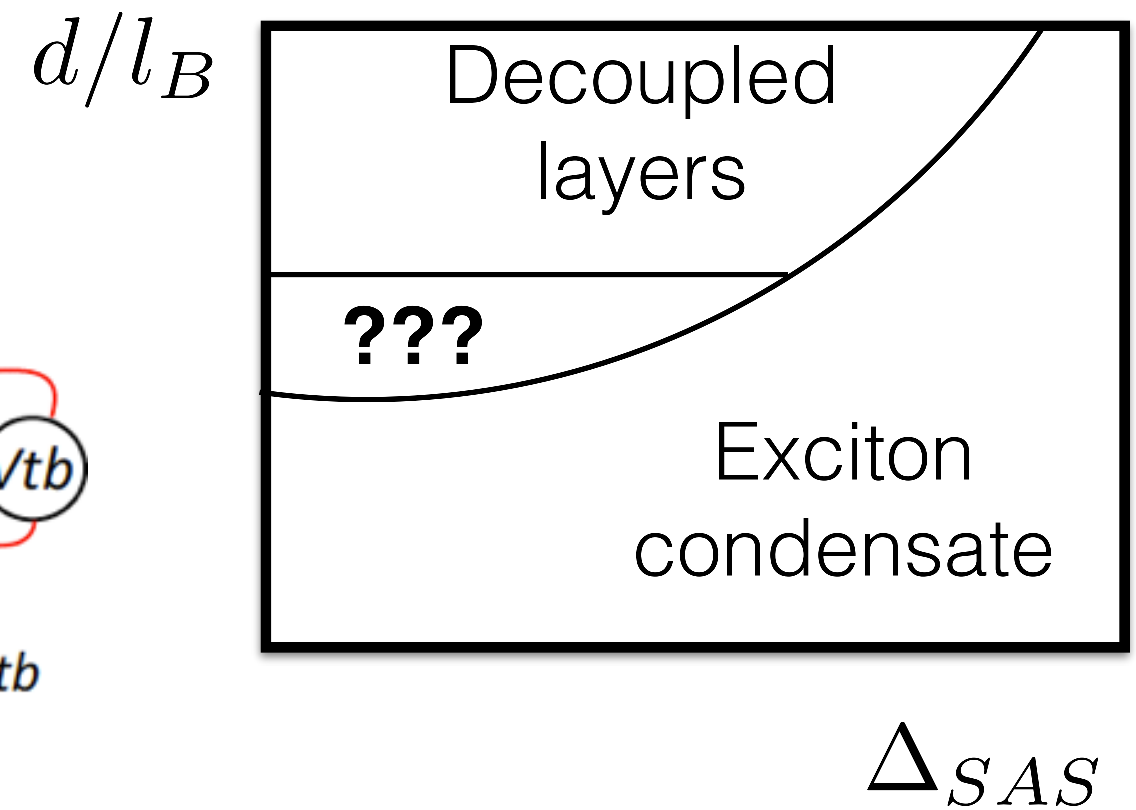


Key question:
Does the charge gap collapses simultaneously with exciton condensate?



Tiemann *et al.*, PRB (2007)



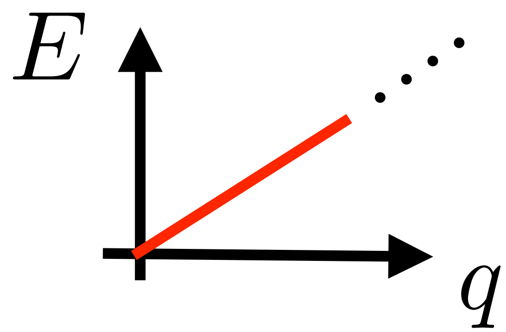


Danke schön!

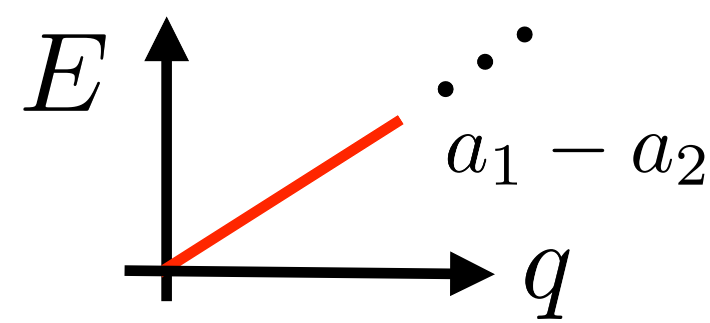
Exciton condensate

Composite fermion superconductor

Spin-wave



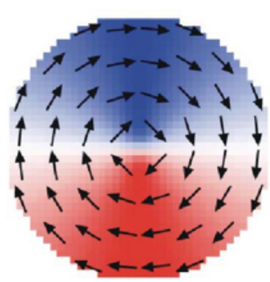
Photon



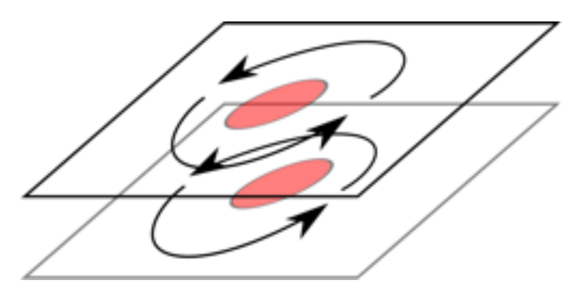
XY vortex

$Q = 1/2$

2π winding



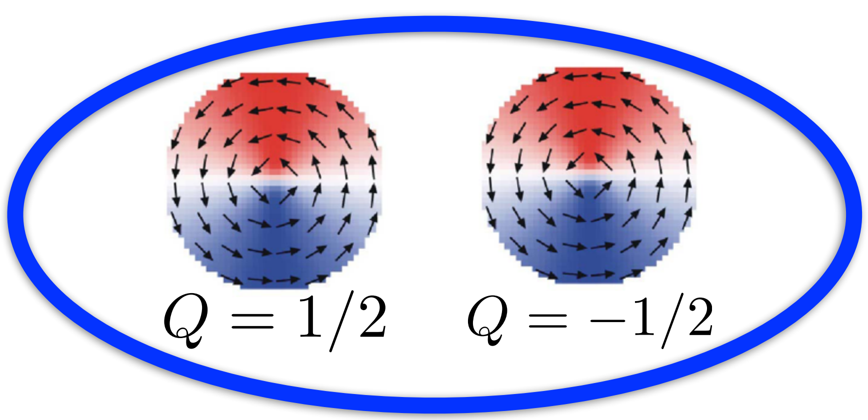
Abrikosov vortex



π flux

$Q = 1/2$

4π **neutral vortex**



Composite fermion

Charge neutral
Dipole carrying

I. Sodemann, I. Kimchi, C. Wang, T. Senthil, Phys. Rev. B **95**, 085135 (2017).

Claim: Interlayer CT-invariant (p_x+ip_y) paired state equals exciton condensate

- Interlayer pairing is:

$$\hat{\Delta} = i\psi^\dagger \sigma_y \tau_x \psi^\dagger \sim i\psi^\dagger_{\text{top}} \sigma_y \psi^\dagger_{\text{bottom}}$$

- In HLR picture this channel corresponds to p_x+ip_y interlayer paring:

$$\hat{\Delta} \sim i\psi^\dagger \tau_x (p_x + ip_y)\psi^\dagger$$

$$\Psi = \Phi_{BCS}(\{z_i, w_j\}) \prod_{i<j}(z_i - z_j)^2 \prod_{i<j}(w_i - w_j)^2$$

$$\Phi_{BCS} \sim \frac{|top\rangle_i |bottom\rangle_j + |bottom\rangle_i |top\rangle_j}{\bar{z}_i - \bar{w}_j}$$