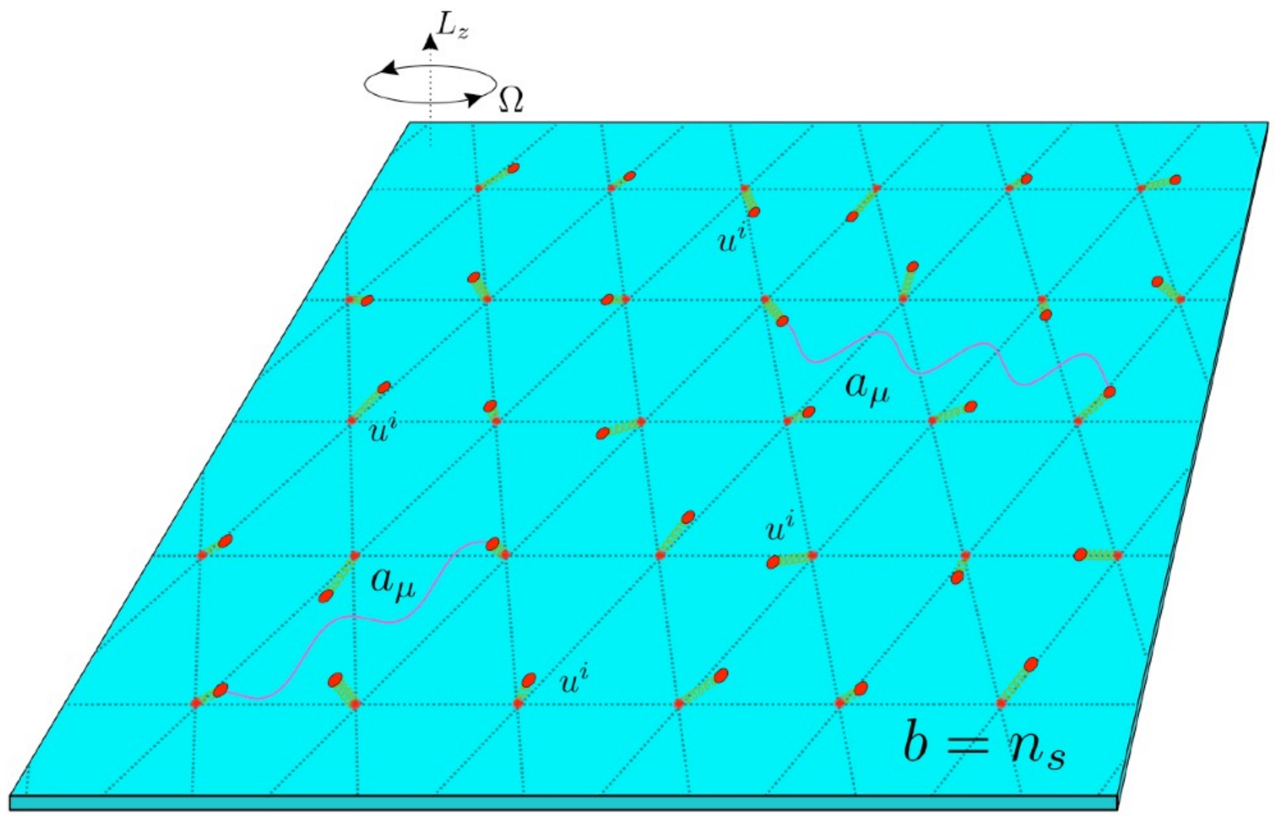
Bosonic superfluid on lowest Landau level



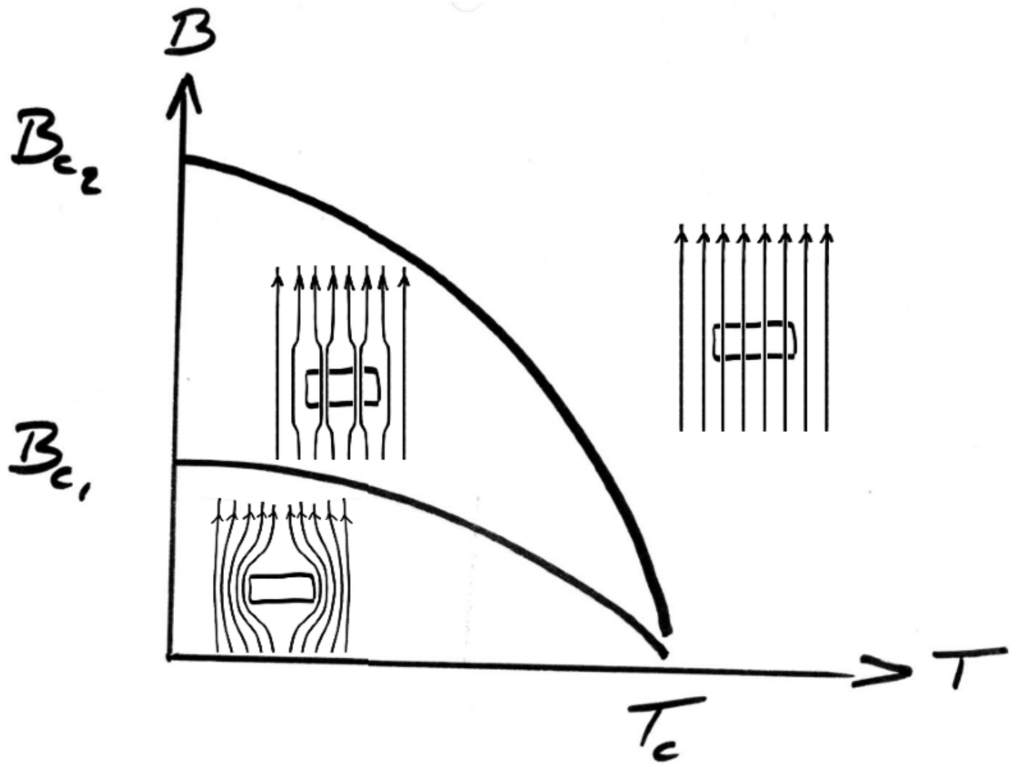
Sergej Moroz
Carlos Hoyos (Oviedo)
Claudio Benzoni (TUM)
Dam Son (UChicago)

TECHNISCHE UNIVERSITÄT MÜNCHEN

arXiv: 1901.06088
SciPost 5, 039 (2018)

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Type II superconductors

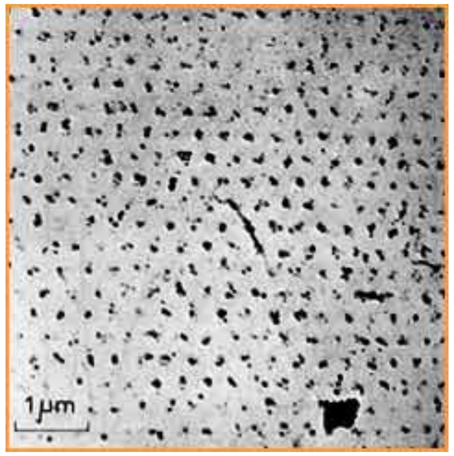


$$\xi < \sqrt{2}\lambda$$

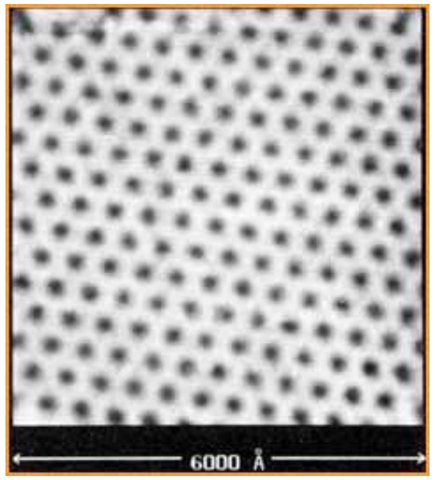
Wikipedia

Lattice of vortices in magnetic field

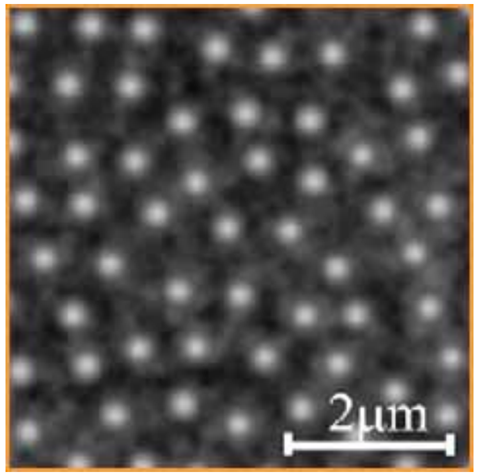
Abrikosov 1957



Stuttgart 1967



Bell Labs 1989



Leuven 2002

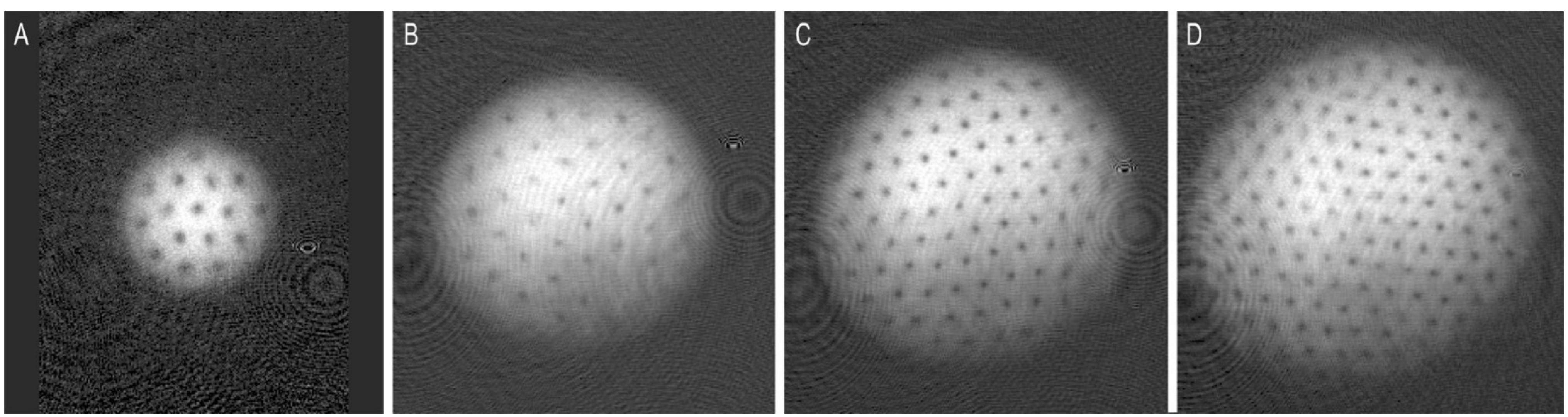
Rotating superfluid

Ground state: minimize the Hamiltonian in rotating frame

$$H = H_{SF} - \Omega L$$

Vorticity of superfluid is carried by quantum vortices *Onsager, Feynman*

Experiments: Helium in 1970's, cold atoms BECs in 2000's



MIT 2001

Rotating superfluid

Superfluid mimics rotating solid body $n_v = \frac{m\Omega}{\pi}$

$n_b \gg n_v$ ⟶ Vortex lattice phase

Theory: Foundations laid by Abrikosov and Tkachenko

Baym, Fetter, Sonin, …

$n_b \ll n_v$ ⟶ Vortex lattice melts, strongly correlated bosonic phases

Cooper 2008
Viefers 2008

Two approaches

Gross-Pitaevskii solutions for vortex crystal

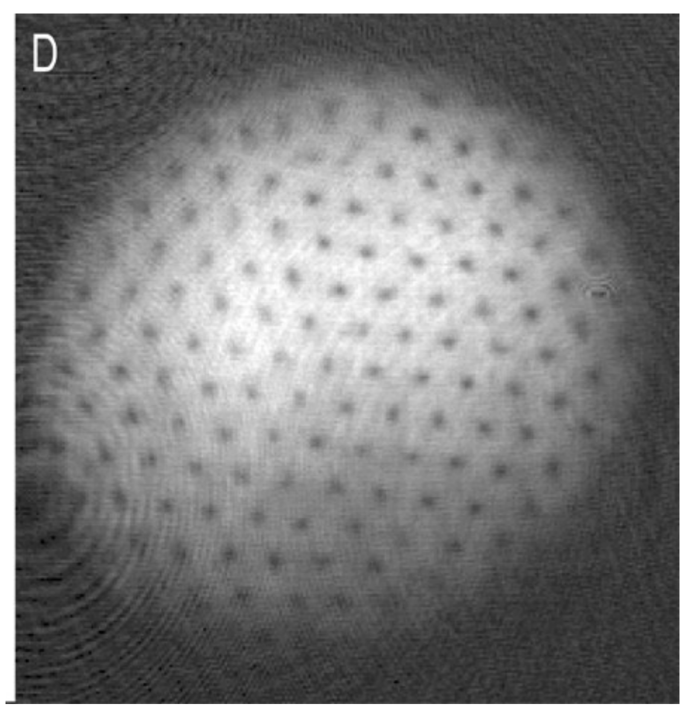
$n_v \xi^2 \ll 1$

Thomas-Fermi regime:
neglect density variations

$n_v \xi^2 \gg 1$

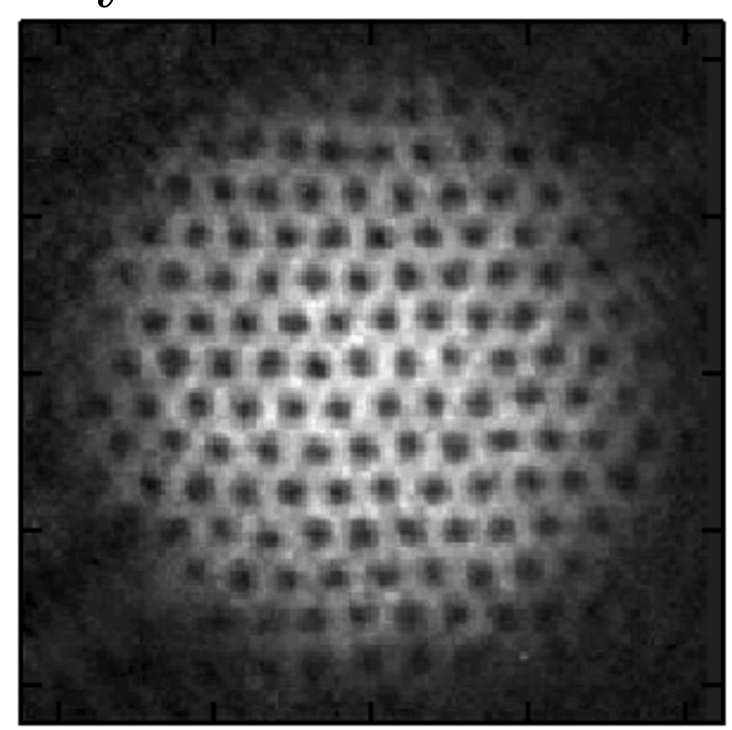
LLL regime:

$$\psi = \prod_i (z - z_i) e^{-|z|^2/4}$$



MIT

Tkachenko solution

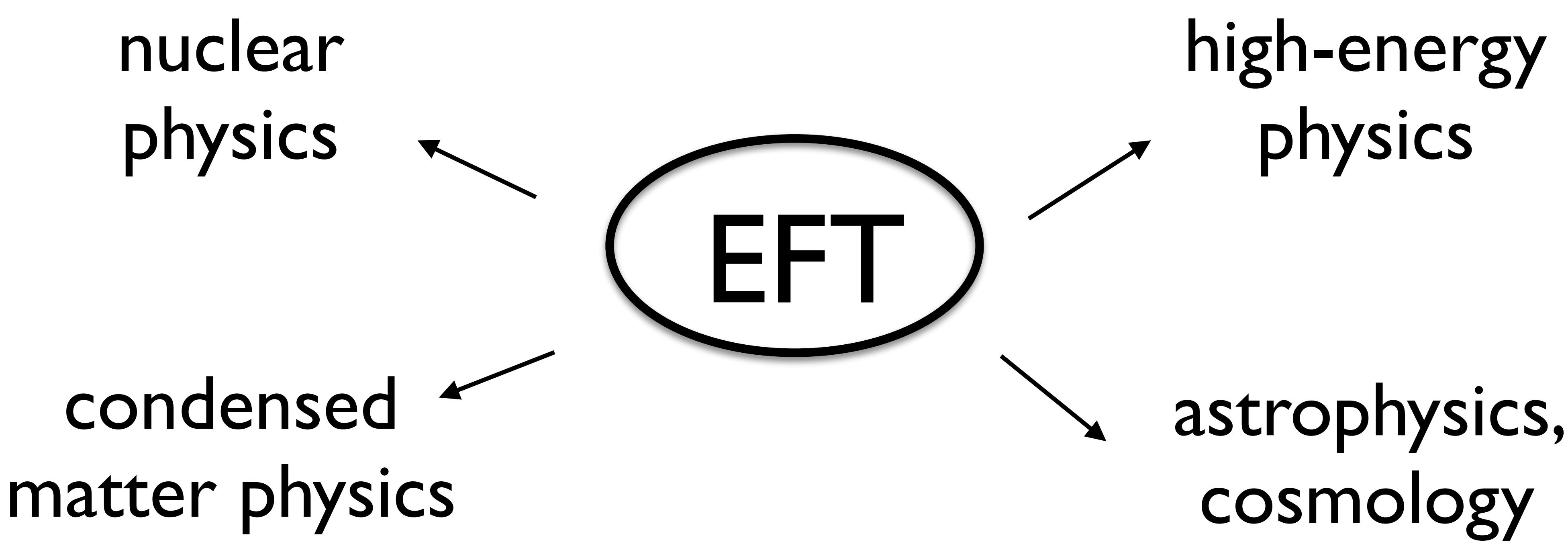


JILA

Abrikosov solution

Effective field theory

- Proper low-energy degrees of freedom
- Respects all symmetries
- Non-perturbative in interactions
- Excitations and linear response are easy



Single vortex dynamics

Not Newtonian, but first time derivative

$$L(X, Y) = \hbar \pi n_s (X\dot{Y} - Y\dot{X})$$

$$[X, Y] = \frac{i}{2\pi n_s}$$

← reason for quantum melting

Transverse "Lorentz" force in magnetic field proportional to superfluid density

Boson-vortex duality

Peskin 1978
Dasgupta&Halperin 1981

To add vortices use boson-vortex duality:

$$j^\mu = \epsilon^{\mu\nu\rho}\partial_\nu a_\rho$$

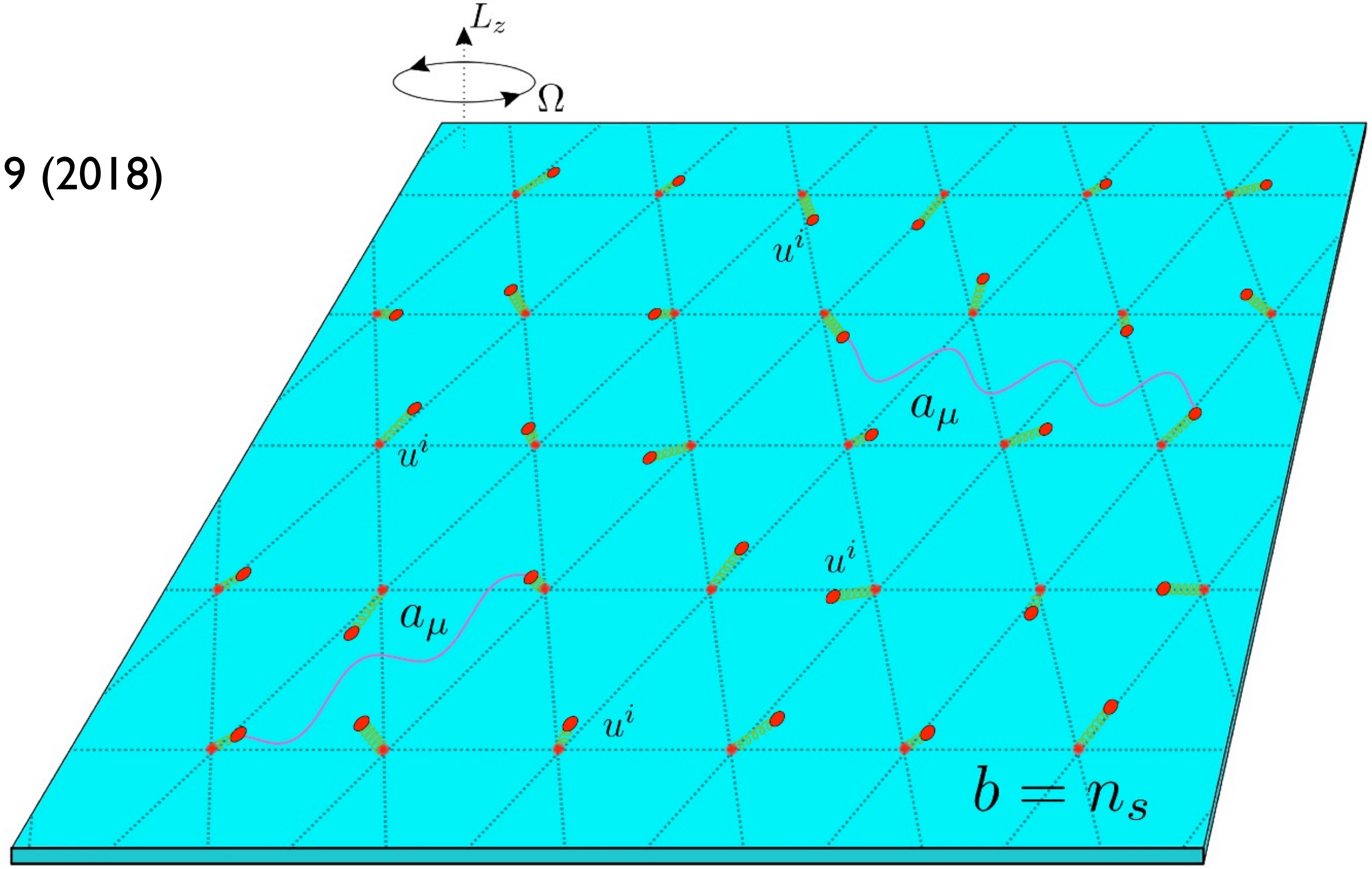
Duality dictionary:

XY model	Abelian Higgs model
$\mathcal{L}_{XY}(\psi)$	$\mathcal{L}_{AH}(v, a_\mu)$
boson ψ	instanton of a_μ
vortex of ψ	charged Higgs v
superfluid density	magnetic field of a_i
superfluid current	electric field of a_μ
superfluid phonon	photon

EFT for slow rotation

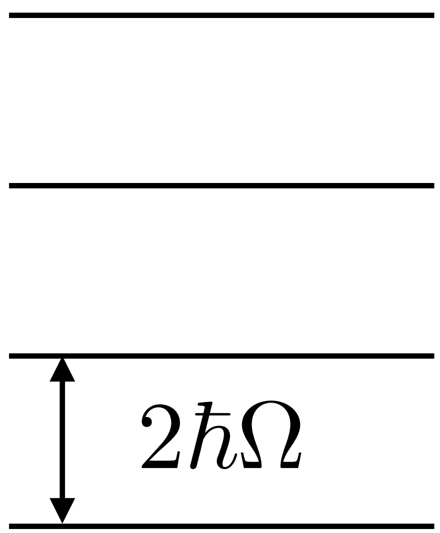
$$\mathcal{L} = \frac{m\mathbf{e}^2}{2b} - \varepsilon(b) - m\Omega b \epsilon_{ij} u^i D_t u^j + 2m\Omega e_i u^i - \mathcal{E}_{\text{el}}(u^{ij}) - \epsilon^{\mu\nu\rho}\mathcal{A}_\mu \partial_\nu a_\rho$$

SciPost **5**, 039 (2018)



dual Wigner crystal in background magnetic field $b = n_s$

LLL regime



Decouple higher Landau levels

$$\Omega \to \infty$$

Density of vortices: $n_v = \dfrac{m\Omega}{\pi}$

Finite density of vortices in the LLL regime

$$m \to 0$$

But what governs superfluid dynamics?

EFT of LLL superfluid

Free bosonic action

$$\mathcal{L}_0 = \frac{i}{2}\psi^\dagger \overleftrightarrow{D}_t \psi - \frac{2}{m} D_z \psi^\dagger D_{\bar{z}} \psi + (\mathrm{g} - 2)\frac{B}{4m}\psi^\dagger \psi$$

EFT of LLL superfluid

Free bosonic action

$$\mathcal{L}_0 = \frac{i}{2}\psi^\dagger \overleftrightarrow{D_t}\psi - \chi^\dagger D_{\bar{z}}\psi - \chi D_z \psi^\dagger + \frac{m}{2}\chi^\dagger\chi + (\mathrm{g}-2)\frac{B}{4m}\psi^\dagger\psi$$

EFT of LLL superfluid

Free bosonic action

$$\mathcal{L}_0 = \frac{i}{2}\psi^\dagger \overleftrightarrow{D}_t \psi - \chi^\dagger D_{\bar{z}}\psi - \chi D_z \psi^\dagger + \cancel{\frac{m}{2}\chi^\dagger}\chi + (\mathrm{g} - \cancel{2)\frac{B}{4m}}\psi^\dagger\psi$$

EFT of LLL superfluid

Free bosonic action

$$\mathcal{L}_0 = \frac{i}{2}\psi^\dagger \overleftrightarrow{D_t}\psi - \chi^\dagger D_{\bar{z}}\psi - \chi D_z \psi^\dagger + \frac{m}{2}\chi^\dagger\chi + (\mathrm{g}-2)\frac{B}{4m}\psi^\dagger\psi$$

duality transformation

$$\mathcal{L}_0 = \varepsilon^{\mu\nu\rho}A_\mu\partial_\nu a_\rho + \boxed{\frac{1}{2b}e^i\partial_i b}$$

Berry term

Adding density-dependent interactions is simple

Berry term

$$\mathcal{L}_0 = \varepsilon^{\mu\nu\rho} A_\mu \partial_\nu a_\rho + \frac{1}{2b} e^i \partial_i b$$

- First-order in time derivative
- Universal coefficient
- Berry term survives in LLL regime
- Is P and T odd $\longrightarrow$ Hall responses
- Not topological $\longrightarrow$ stress tensor

Angular momentum on LLL

From EFT $$J_z = \int d^2x \epsilon_{ij} x^i T^{0j} = -N$$

\# of bosons

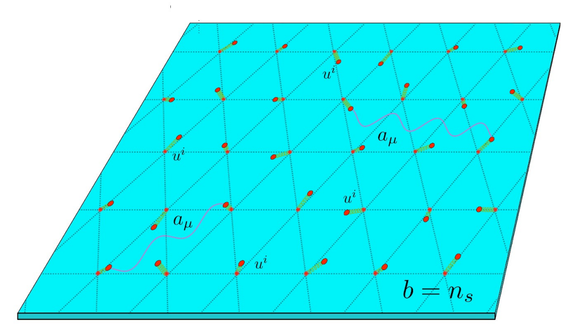
Agrees with LLL wave-function calculation

$$J_z = -i\varepsilon_i^{\ j} x^i D_j = (zD_z - \bar{z}D_{\bar{z}})$$

$$\Psi_{LLL} = f(z) e^{-|z|^2/(4l_B^2)}$$

Collective excitation

Vortex lattice EFT

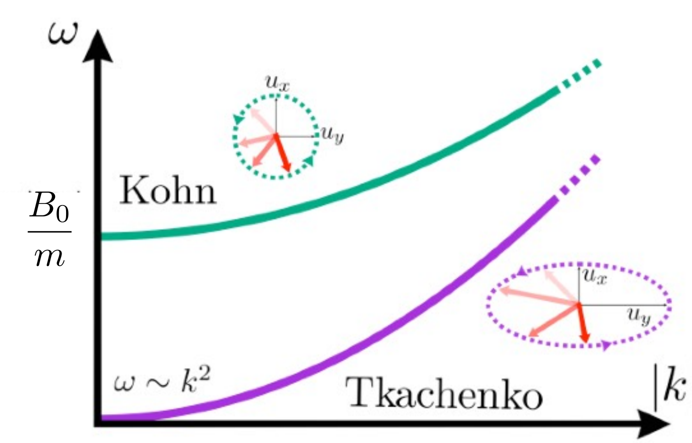


$$\mathcal{L}_{vc} = \frac{me^2}{2b} + \frac{1}{2b} e^i \partial_i b + \epsilon^{\mu\nu\rho} \mathcal{A}_\mu \partial_\nu a_\rho + \frac{(\mathrm{g}-2)}{4m} \mathcal{B} b - \varepsilon(b)$$
$$- \frac{B_0}{2} b \epsilon_{ij} u^i D_t u^j + B_0 e_i u^i - \mathcal{E}_{\text{el}}(u_{ij})$$

Collective dispersion in the LLL limit

$$\omega^2 = \frac{2C_2 \varepsilon''}{B_0^2} k^4 - \frac{2C_2 \varepsilon''}{B_0^3} k^6 + O(k^8)$$

from NLO
Berry term



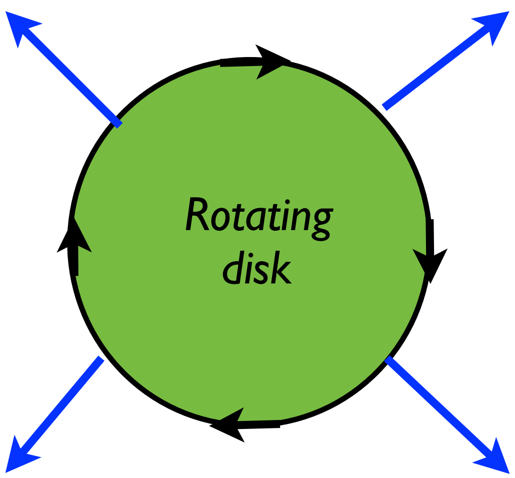
Hall viscosity

Avron, Seiler, Zograf 1995

$$T^{ij} = \eta^{ijkl}\dot{u}_{kl}$$

- Time-reversal breaking $\quad \eta_{odd}^{ijkl} = -\eta_{odd}^{klij}$
- Non-dissipative force

$$f^i_{\text{Hall}} = \eta_{\text{H}}\epsilon^{ij}\Delta v_j$$



- In rotation-invariant system

$$\frac{\eta_{\text{H}}}{n} = \frac{\mathcal{S}}{4}$$

Read 2009
Read&Rezayi 2011

Hall responses

from NLO Berry term

Hall conductivity $$\sigma^H(\omega, k) = \frac{n_0}{B_0} - \frac{n_0}{2B_0^2}k^2 + O(k^4)$$

Galilean invariance ties Hall conductivity and viscosity

at g=2 on LLL

$$\eta_H = \frac{1}{2}B_0^2\partial_k^2\sigma_H(k) + \frac{1}{2}B_0\sigma_H(k=0)$$

we also computed Hall viscosity from $\delta T^{ij} = -\eta^{ijkl}\delta\dot{g}_{kl}$

Conclusions

- EFT of vortex crysal: from slow to fast rotation
- Soft collective mode
- Hall conductivity, but no Hall viscosity so far

NORDITA

Effective Theories of Quantum Phases of Matter

6-31 May 2019 | **Nordita, Stockholm**

Home

Venue

More info at: www.nordita.org/eft2019

Registration deadline: February 1