Rotating Bosons

from spin textures to quantum Hall states

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acknowledgements

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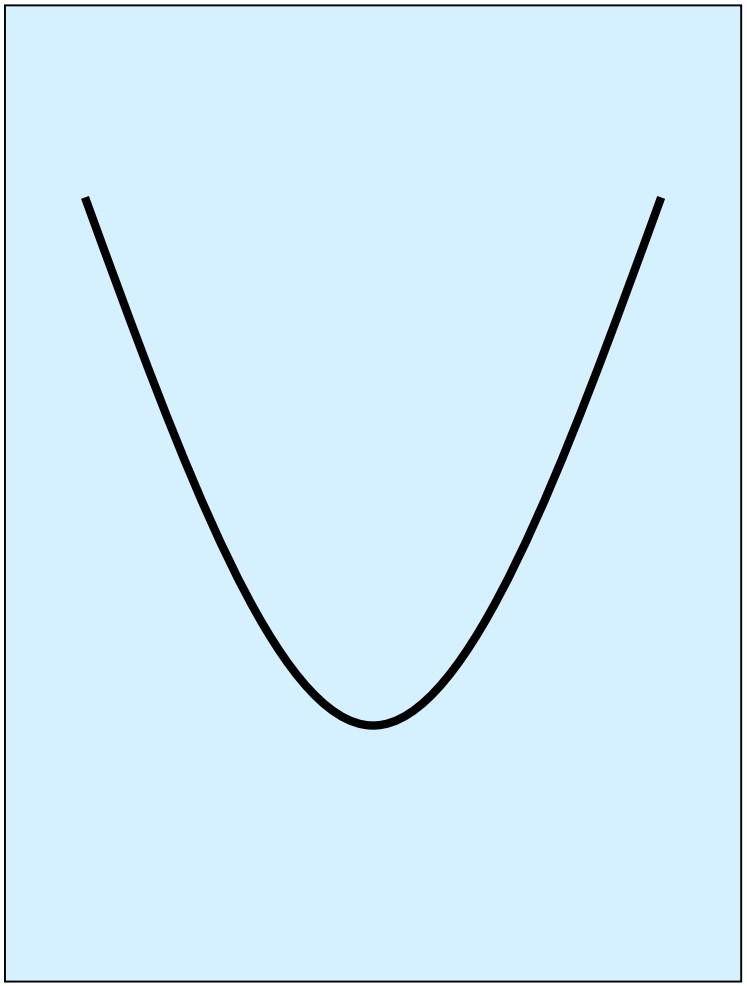
(Cambridge)

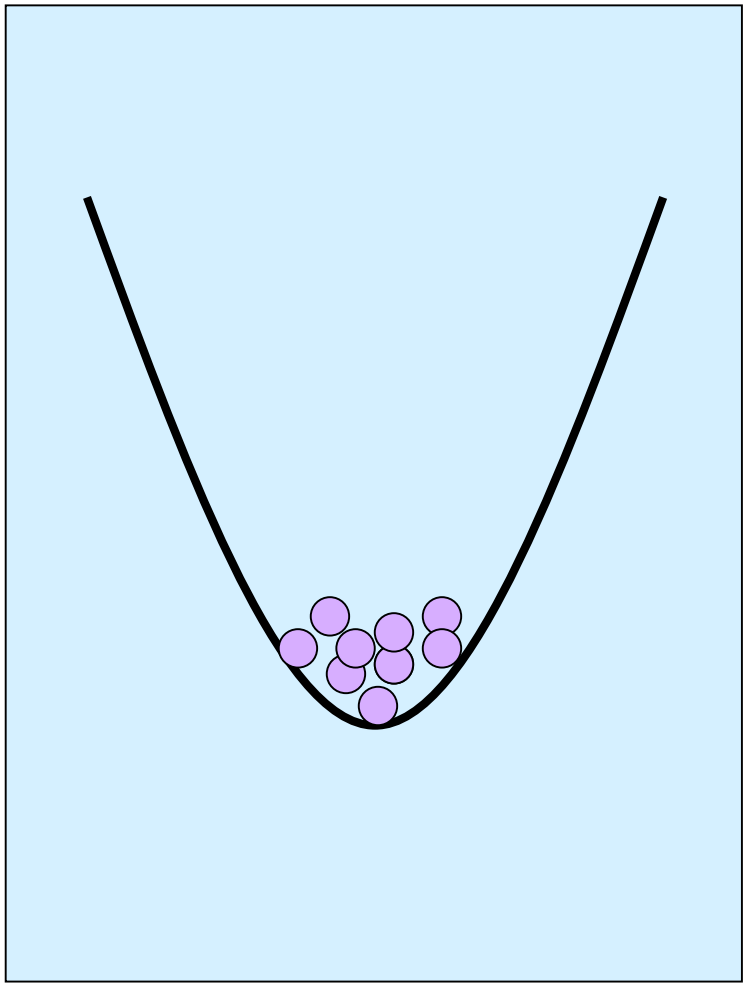
J.W. Reijnders
(UvA)

F.J.M. van Lankvelt
(Oxford)

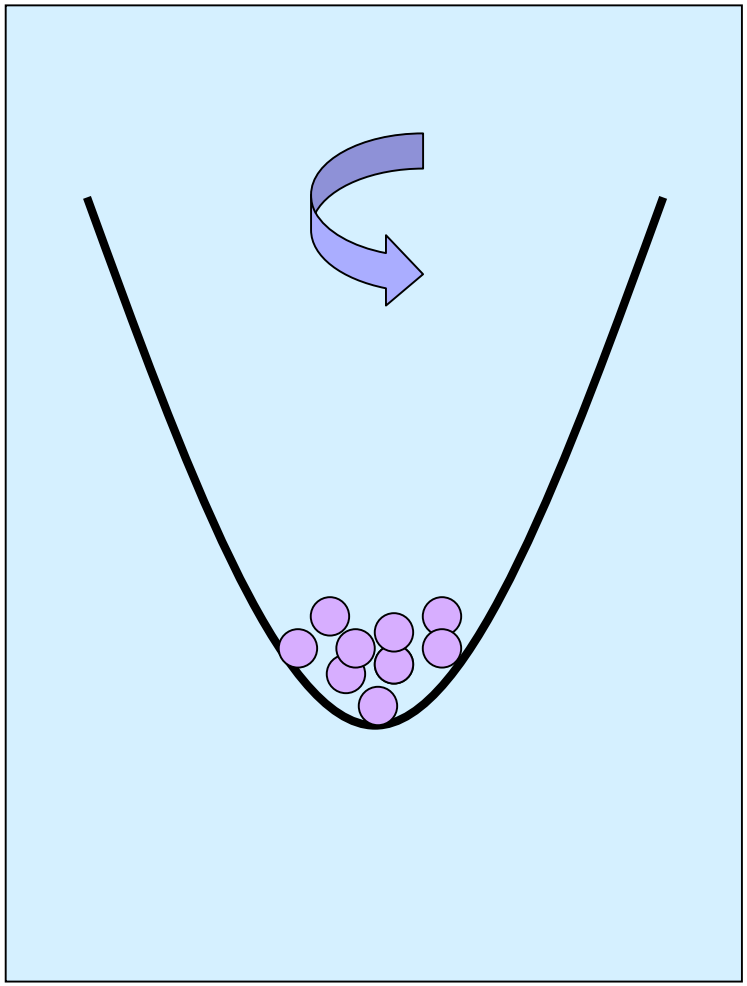
rotating bosons



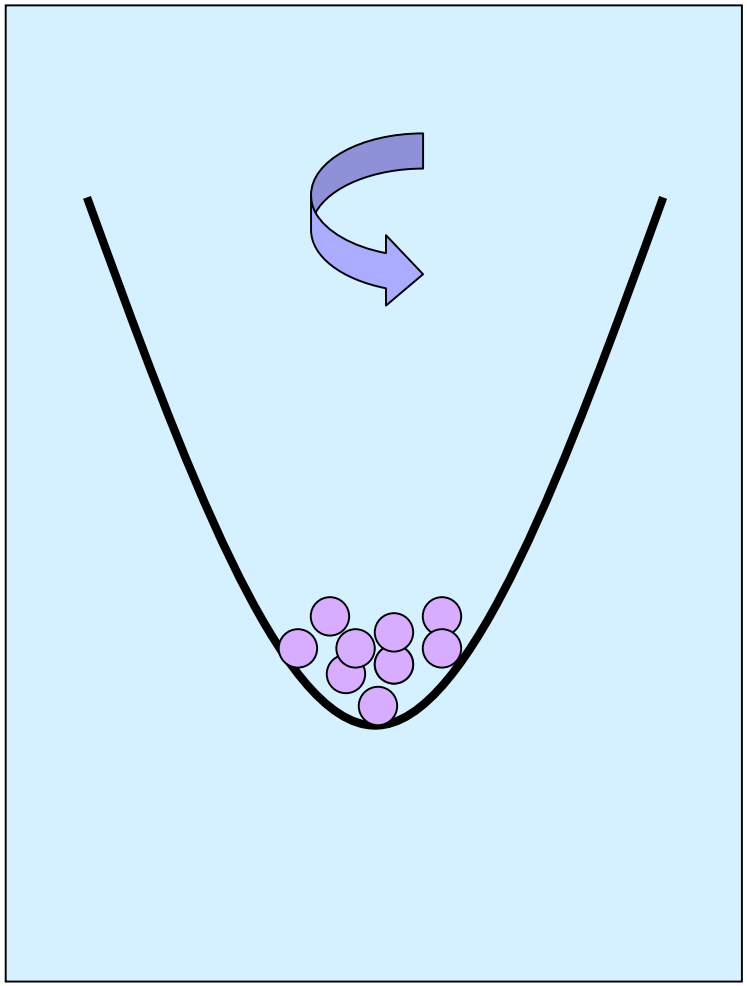
rotating bosons



rotating bosons



rotating bosons

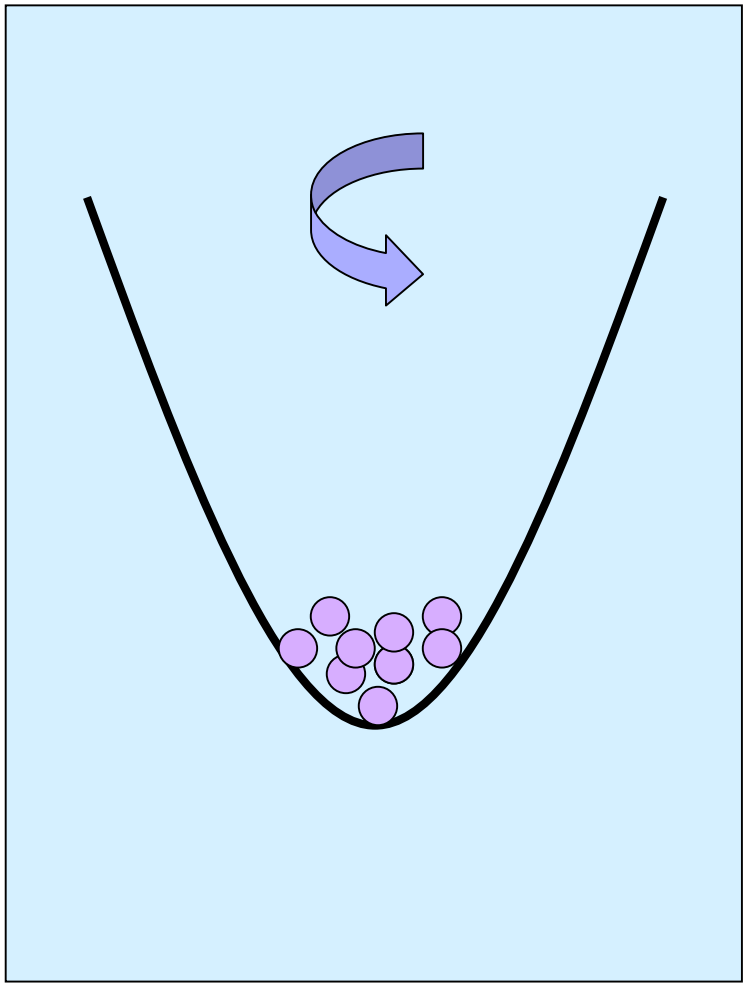


bosonic atoms at

- **low temperature**
- **high density**
- **in a (rapidly) rotating trap**

? what happens ?

atomic (fractional) quantum Hall states



expected: formation of incompressible quantum liquids (`atomic quantum Hall states') for bosons (fermions) at ultra-rapid rotation

why are quantum Hall states expected?

- rotation vs. charged particles in $B_\perp$ in 2D

The hamiltonian for *N* (neutral) bosons (mass *M*) in cylindrical trap with radial and axial trapping frequencies $\omega_\perp$ and ω_z , rotation frequency Ω …

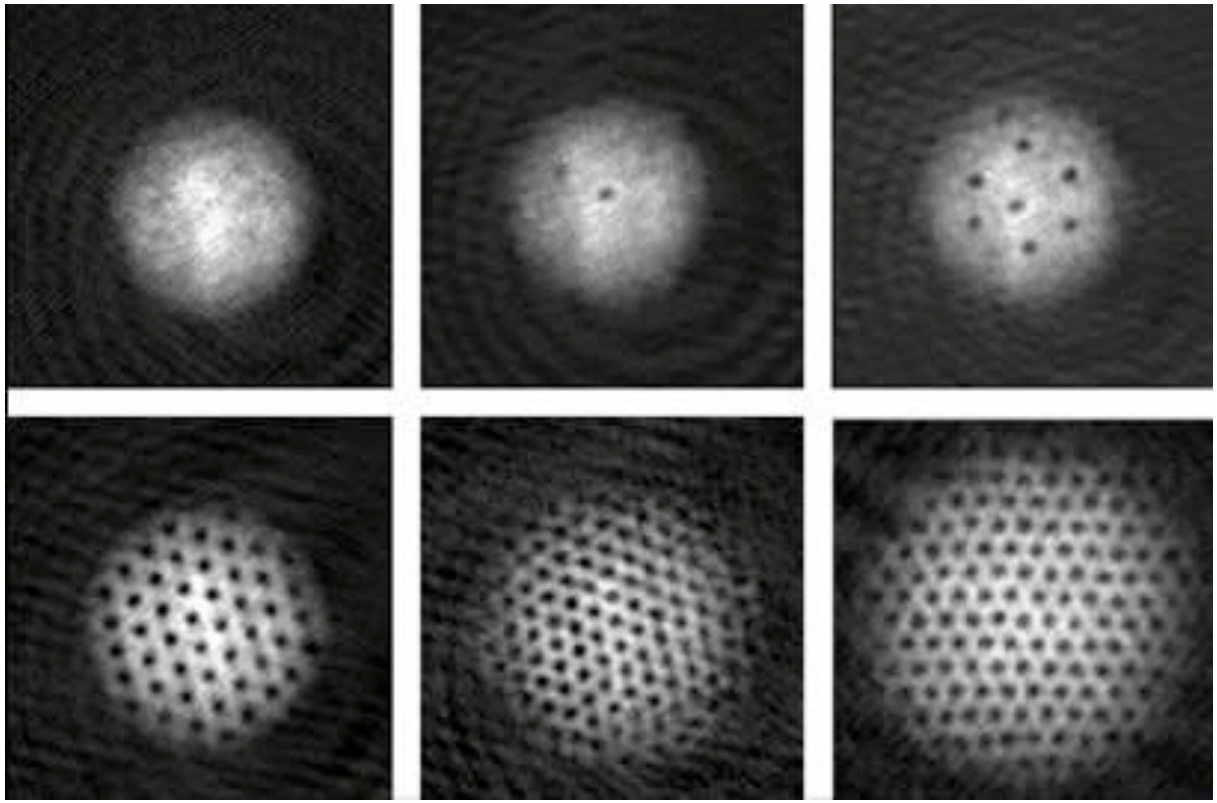
$$H = \sum_{i=1}^{N} \left\{ \frac{(\mathbf{p}_i - M\,\Omega\,\hat{\mathbf{z}}\times\mathbf{r}_i)^2}{2M} + \frac{M}{2}\left[(\omega_\perp^2 - \Omega^2)(x_i^2 + y_i^2) + \omega_z^2 z_i^2\right] \right\} + \sum_{i<j=1}^{N} V(r_i - r_j)$$

… is equivalent to hamiltonian for *N* charged particles in magnetic field $B_\perp = 2\,M\,\Omega$ along the *z*-direction, in a weakened radial confinement.

why have quantum Hall states not been seen?

- challenging the collective behavior

In a quantum regime, bosons tend to form a collective state – the BEC. A rotating BEC accommodates the angular momentum by forming vortices, which order on a triangular lattice.



JILA, 2003

phases of rotating bosons

quantum melting of the vortex lattice at $\nu_c = 6 - 10$

Cooper-Wilkin-Gunn;
Sinova-Hanna-MacDonald

incompressible quantum Hall liquids at specific ν

- Laughlin, MR and RR states at $\nu = k/2$
- hierarchy (CF) states at $\nu = p/(p+1)$

Cooper-Wilkin-Gunn; Regnault-Jolicoeur; …

experiments in rapid rotation regime

Schweikhard et al (JILA), Bretin et al (ENS)

- reaching the 2D regime -- ok
- reaching the Lowest Landau Level (LLL) -- ok
- reaching critical rotation:
  - achieved: up to 300 vortices, $\Omega/\omega_\perp = 0.99\ldots$,
  - need to reduce filling factor from $\nu \sim 500$ to $\nu_c \sim 6 - 10$
- temperature needs to be below the scale g_{qH}

$$g_{\mathrm{qH}} = \frac{g}{(2\pi)^{3/2} l_\perp^2 l_=} \qquad g = \frac{4\pi\hbar^2 a}{m}$$

which is of order 1 – 5 nK.

multi-layer set-up for atomic qH states

proposal (Cornell, Dalibard)

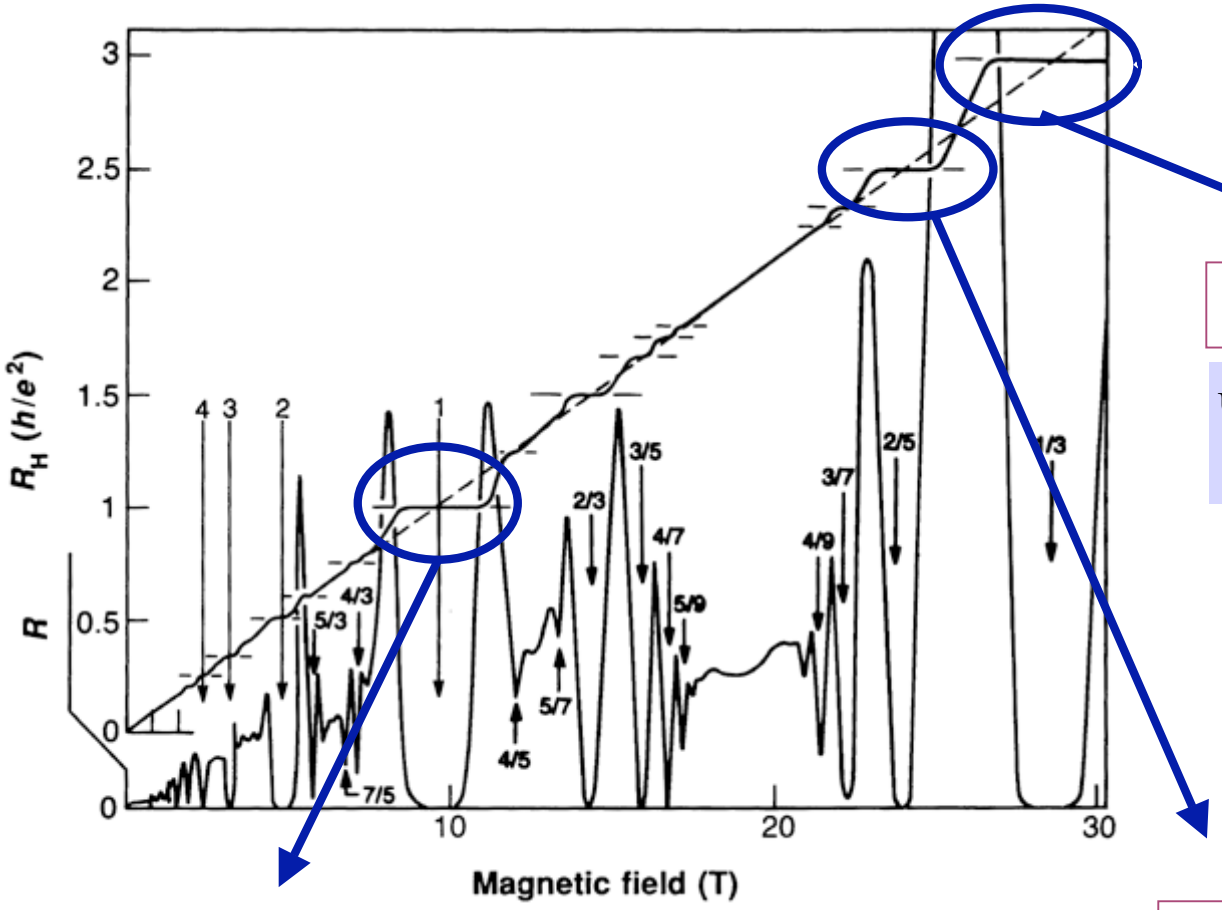
- **achieve desired rotation rates by slicing up a cigar-shaped, rotating condensate with the help of an optical lattice potential**
- **slicing up into N_L layers enhances the filling with a factor N_L. Example**

$$N=5000,\ N_V=100,\ N_L=50:\quad \nu=50 \rightarrow \nu'=1$$

[state of the art (V. Schweikhard) :
$\nu'=100$ **achieved; problems with spin-down upon imposing optical lattice]**

detecting atomic qH states

detecting electronic quantum Hall states



fractional qH state

$$\Psi(z_1,..,z_N) \cong \prod_{i<j} (z_i - z_j)^3$$

integer qH state

$$\Psi(z_1,..,z_N) \cong \prod_{i<j} (z_i - z_j)$$

`hierarchy' state

detecting atomic qH states

many ideas :

- **density correlations after expansion**
- **edge modes**
- **vanishing of condensate fraction**
- **(fractional) braiding of bulk excitations**
- **…**

we propose to detect atomic quantum Hall states via characteristic density profiles, in single-layer or multi-layer geometry

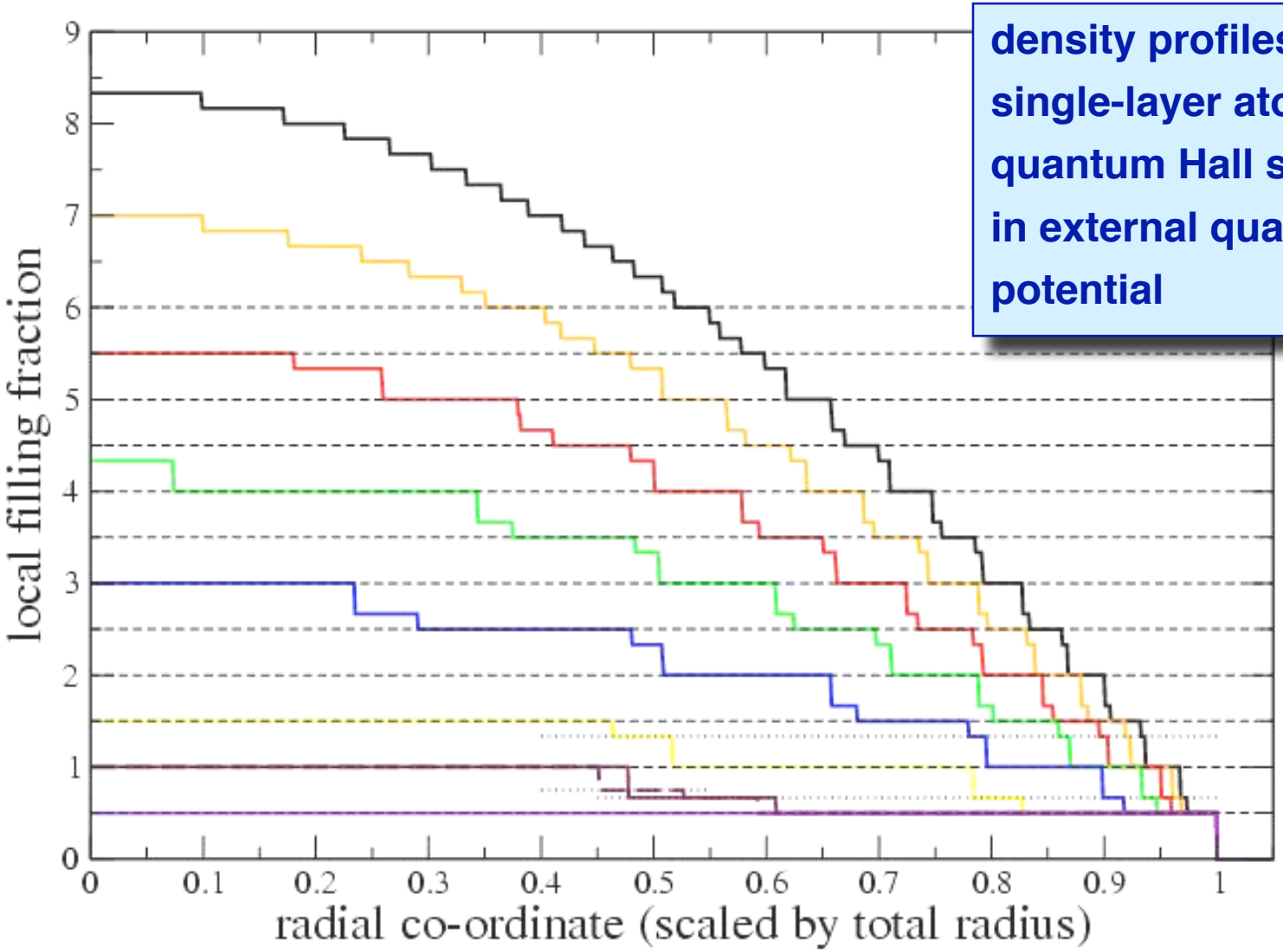
N. R. Cooper, F.J.M. van Lankvelt, J.W. Reijnders, KjS, cond-mat/0409146; Phys. Rev. A72 (2005) 063622

density profiles for atomic qH states

in the presence of confining potential, there will be non-uniform density of the quantum liquid; to minimize the energy, the system will phase separate into patches with incompressible quantum Hall liquids

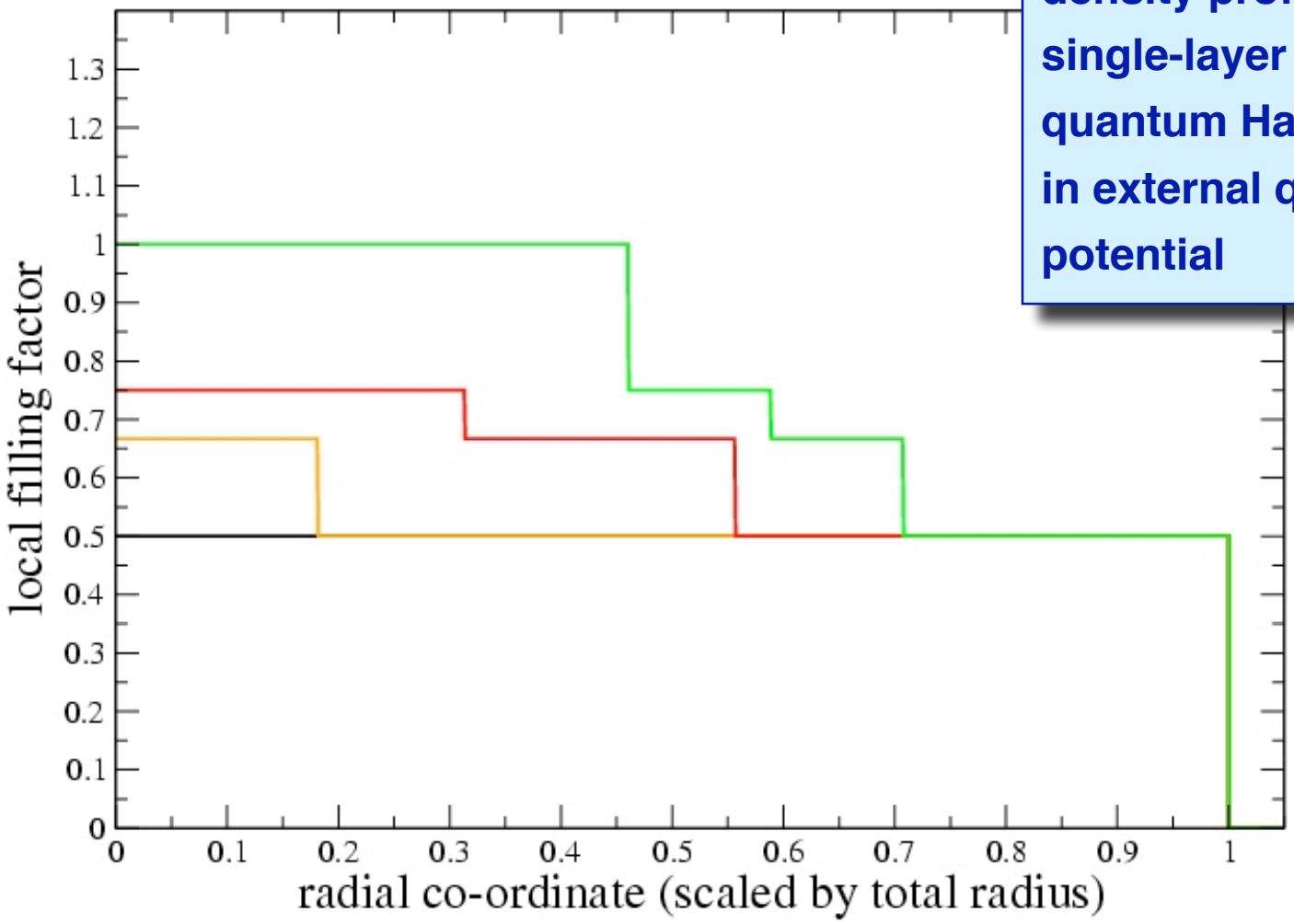
for a single layer, this gives a 2D landscape with steps; a multi-layer system will have such landscapes in each individual layer

single layer density profiles



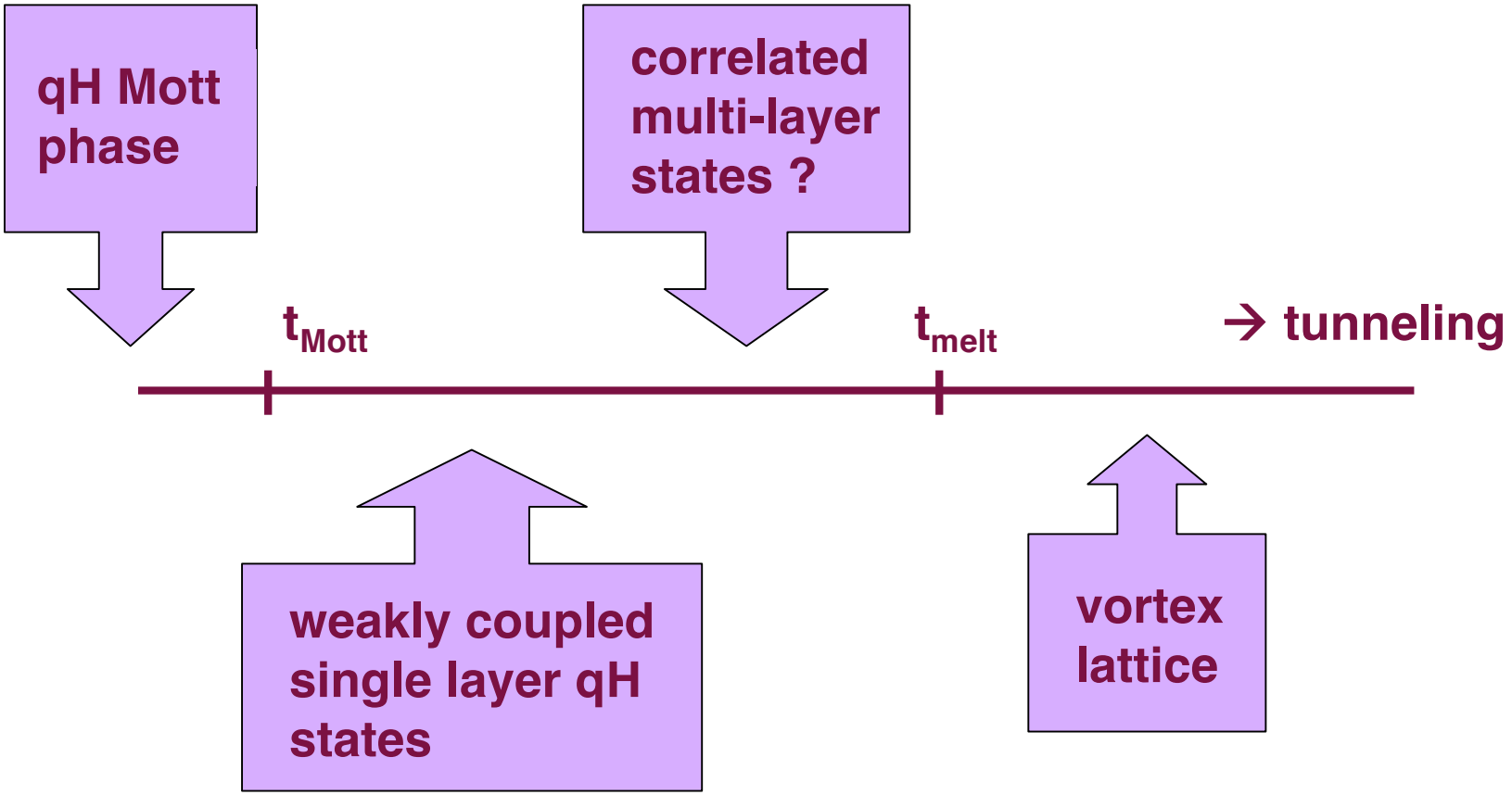
density profiles of single-layer atomic quantum Hall states in external quadratic potential

single layer density profiles (II)

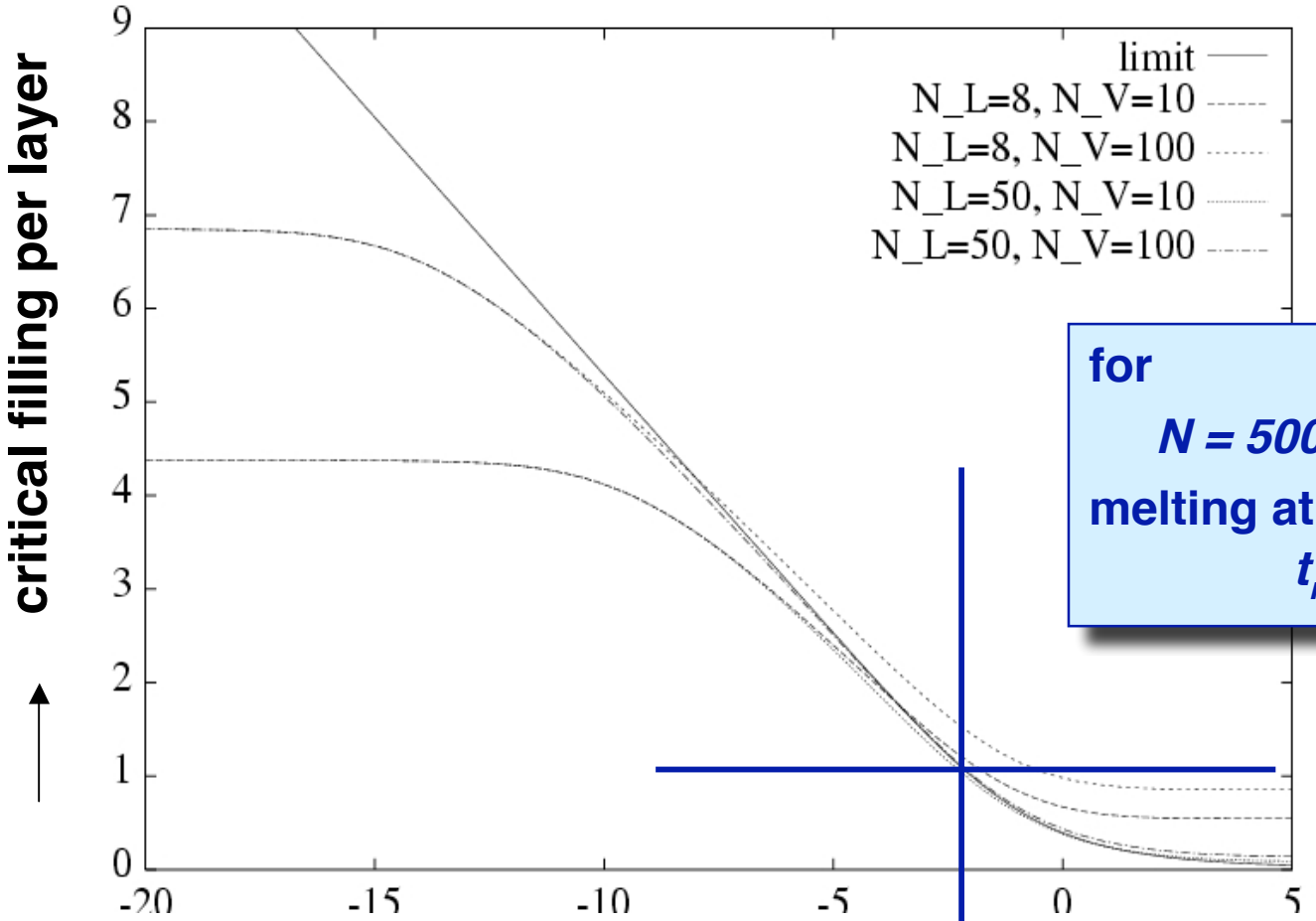


density profiles of single-layer atomic quantum Hall states in external quadratic potential

phases of the multi-layer system



melting of the vortex lattice in multi-layer set-up



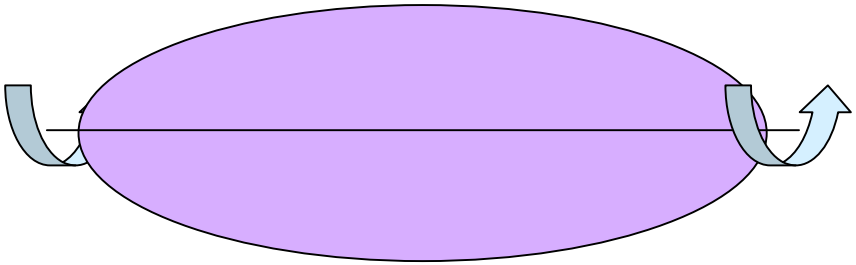
for

$N = 5000$, $N_V = 100$, $N_L = 50$

melting at

$t_{melt} = .18\ g_{qH}$

multi-layer set-up and detection



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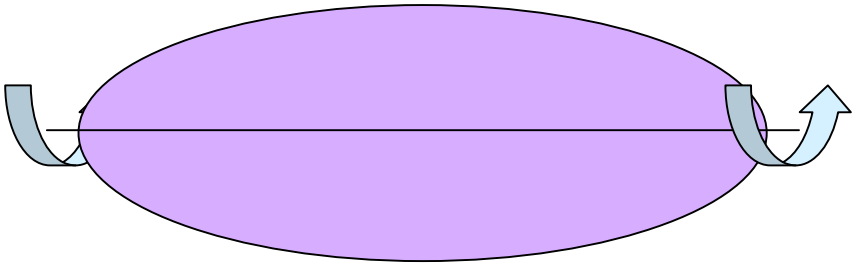
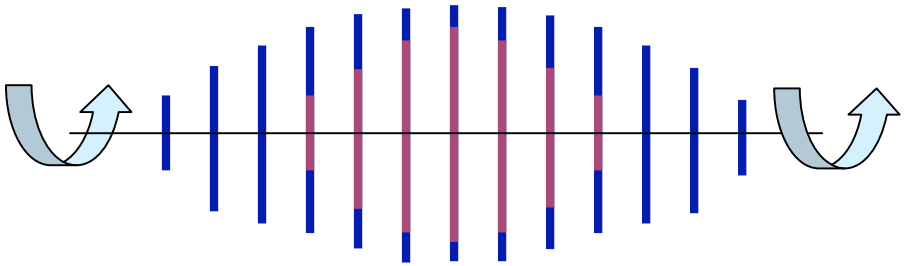


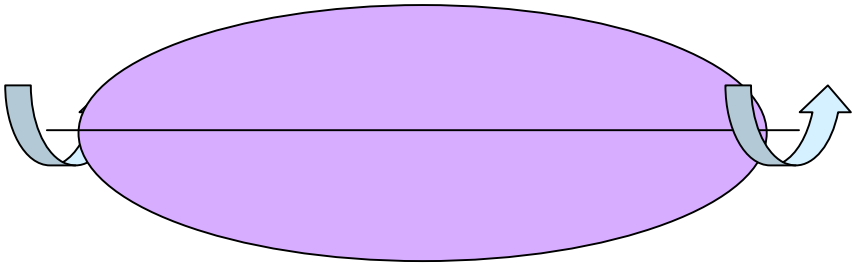
slicing w/t
optical lattice



Laughlin state, $\nu = 1/2$

hierarchy state, $\nu = 2/3$

multi-layer set-up and detection



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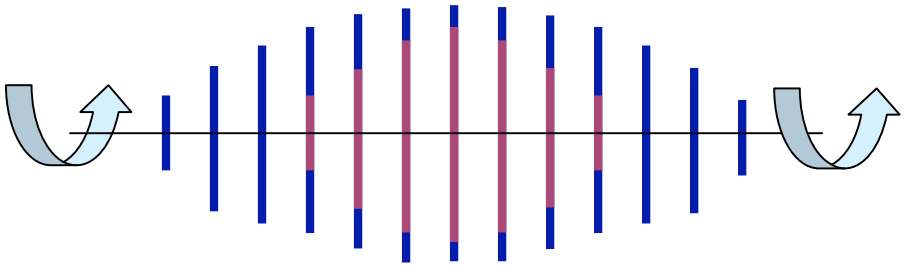
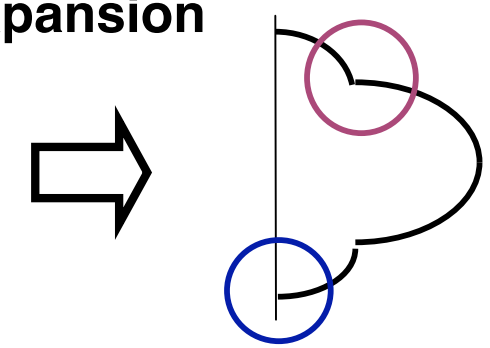


expansion



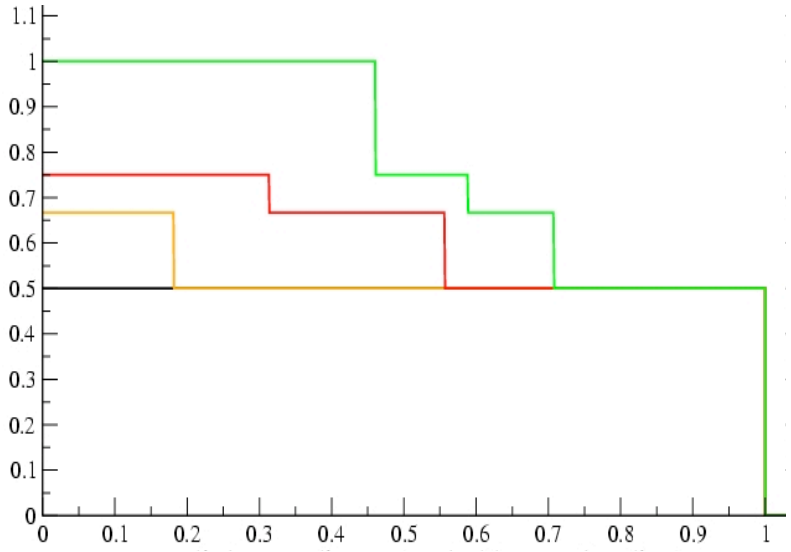
Laughlin state, $\nu = 1/2$

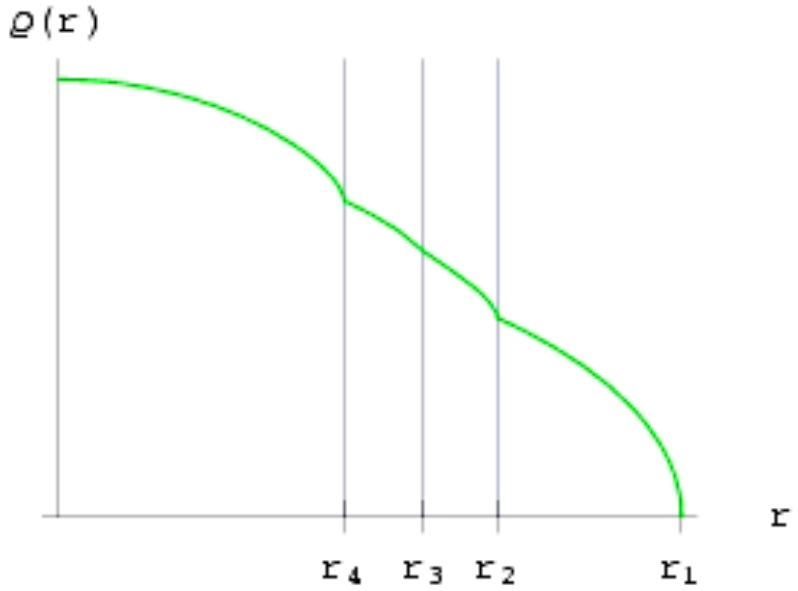
hierarchy state, $\nu = 2/3$

density profile $\rho(r)$

cusps in radial density profile after expansion

as remnants of the steps of the density profile in individual layers, the radial profiles after expansion shows cusps

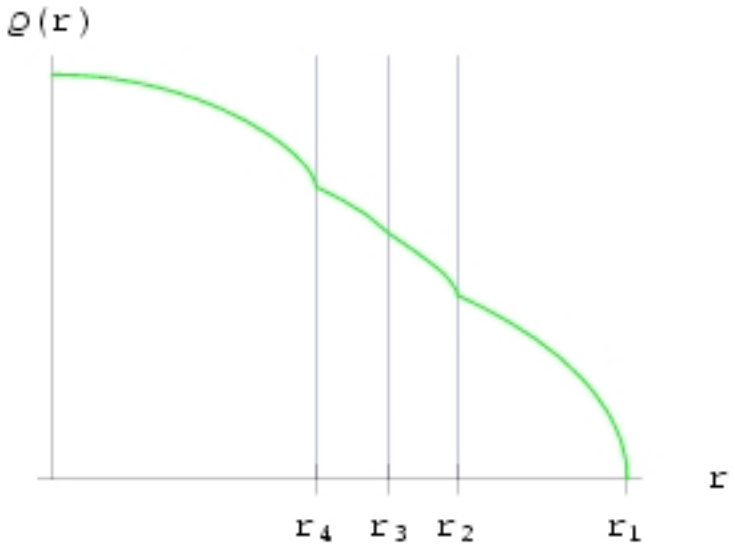




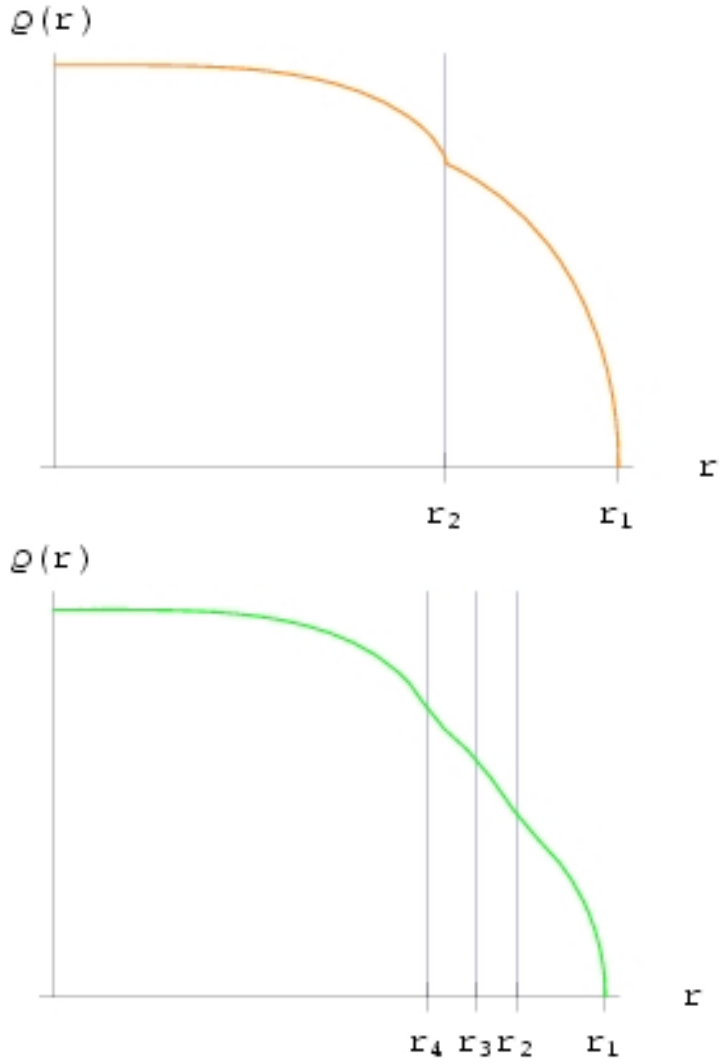
steps in central layer **vs** **profile after expansion**

cusps in radial density profile after expansion

cusps become more pronounced if radial and/or axial confinement are steeper than quadratic.

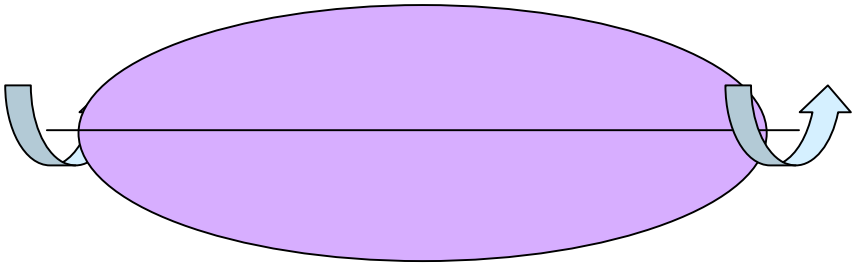


quadratic radial confinement

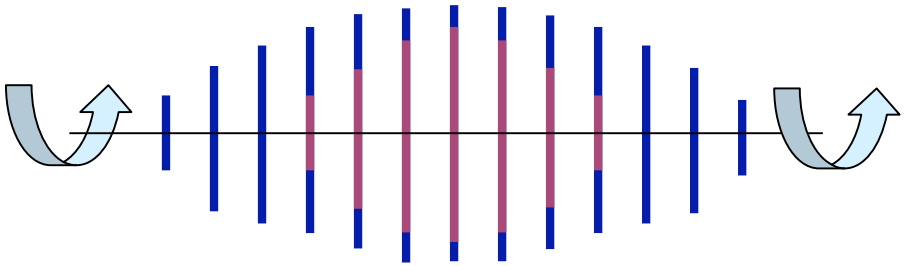


quartic radial confinement

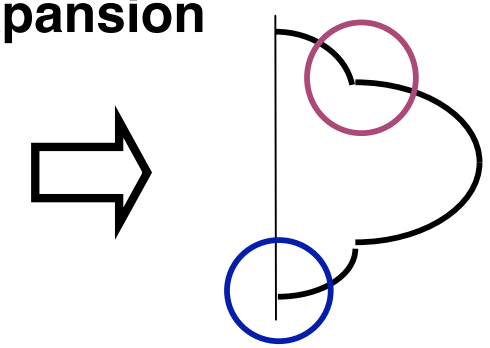
Summary: multi-layer set-up and detection of atomic quantum Hall states



slicing w/t
optical lattice



expansion



Laughlin state, $\nu = 1/2$

hierarchy state, $\nu = 2/3$

density profile $\rho(r)$
with characteristic
features (cusps)