Quantum phase transition in an atomic Bose gas with Feshbach resonances

M.W.J. Romans (Utrecht)

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cond-mat/0312446

See also L. Radzihovsky, J. Park , P. Weichman, cond-mat/0312237.

Exotic order in an atomic Bose gas with Feshbach resonances

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- Can we connect two states by adiabatic evolution of a coupling constant ?

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A quantum phase transition must occur if the states have

• distinct “conventional” order parameters/broken symmetry

• distinct “quantum/topological/exotic” order with distinct quantum numbers of excitations

Fermi gas near a Feshbach resonance

BEC of molecules

BCS state of paired fermions

detuning

Fermi gas near a Feshbach resonance

$$\Psi = \text{Antisym}\left[\prod_{\text{pairs } i,j} \phi_m\left(r_{i\uparrow} - r_{j\downarrow}\right)\right]$$

BEC of molecules

BCS state of paired fermions

detuning

Smooth crossover between two limits;
Different theories can be judged only by their quantitative accuracy.

Bose gas near a Feshbach resonance

BEC of molecules

BEC of atoms

detuning

<u>Bose</u> gas near a Feshbach resonance

$$\Psi = \mathrm{Sym}\left[\prod_{\text{pairs } i,j} \phi_m\left(r_i - r_j\right)\right]$$

$$\Psi = \prod_{\text{atoms } i} \phi_a\left(r_i\right)$$

BEC of molecules

BEC of atoms

detuning

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Bose gas near a Feshbach resonance

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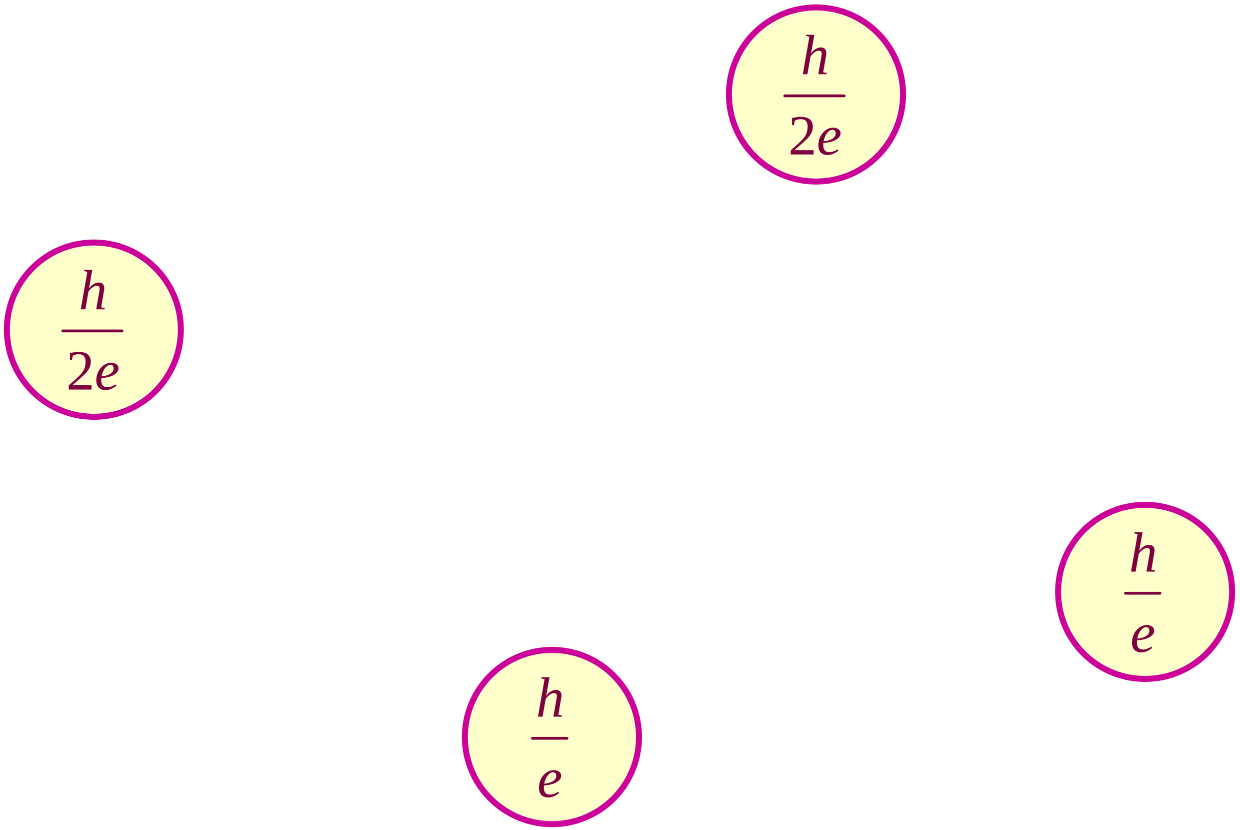
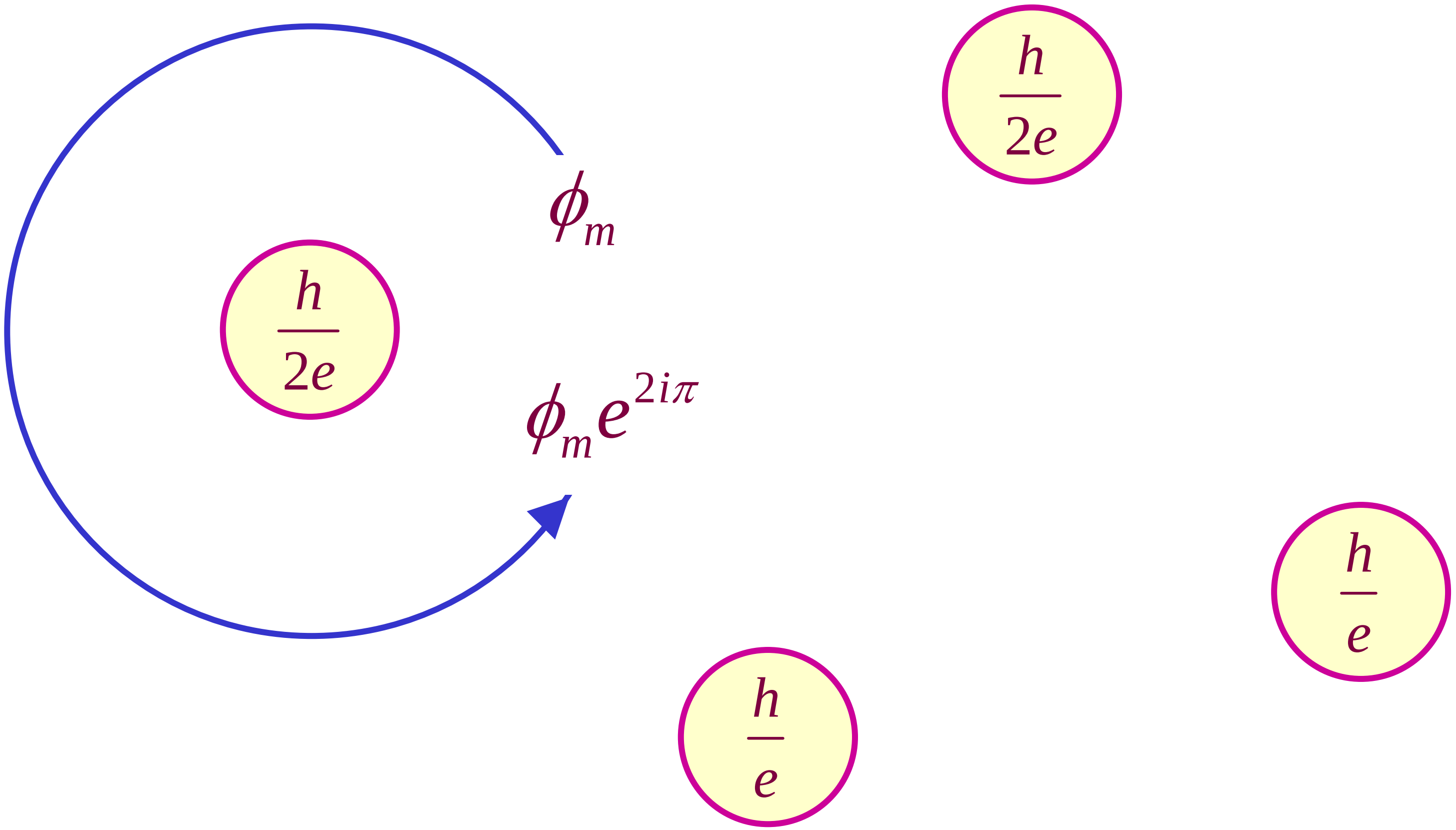
We (Romans *et al.* cond-mat/0312446 and Radzihovsky *et al.* cond-mat/0312337) argued for the necessity of a quantum phase transition between two distinct superfluids which are distinguished by an Ising quantum order.

Why are the two superfluids distinct ?



Vortices in a molecular superfluid

Why are the two superfluids distinct ?



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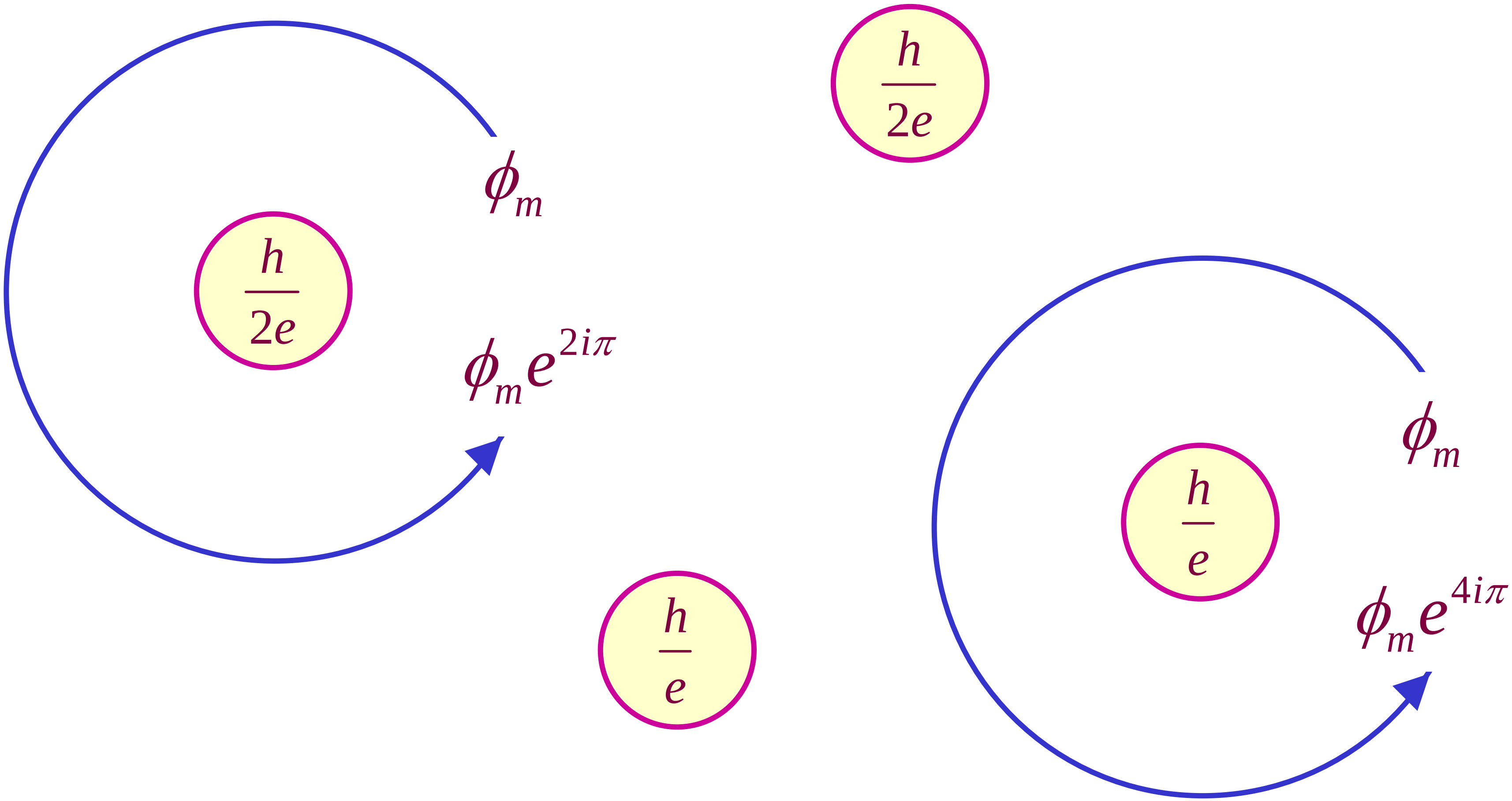

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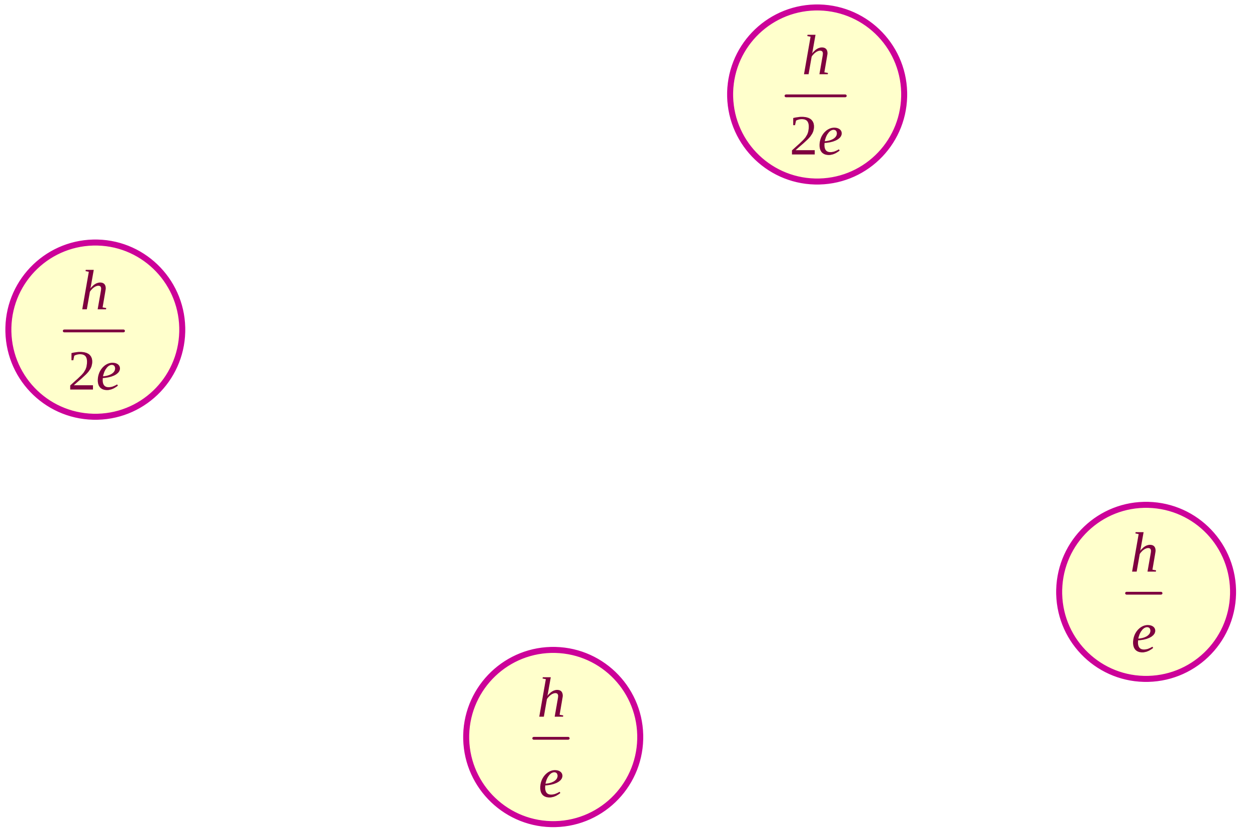

Vortices in an atomic superfluid

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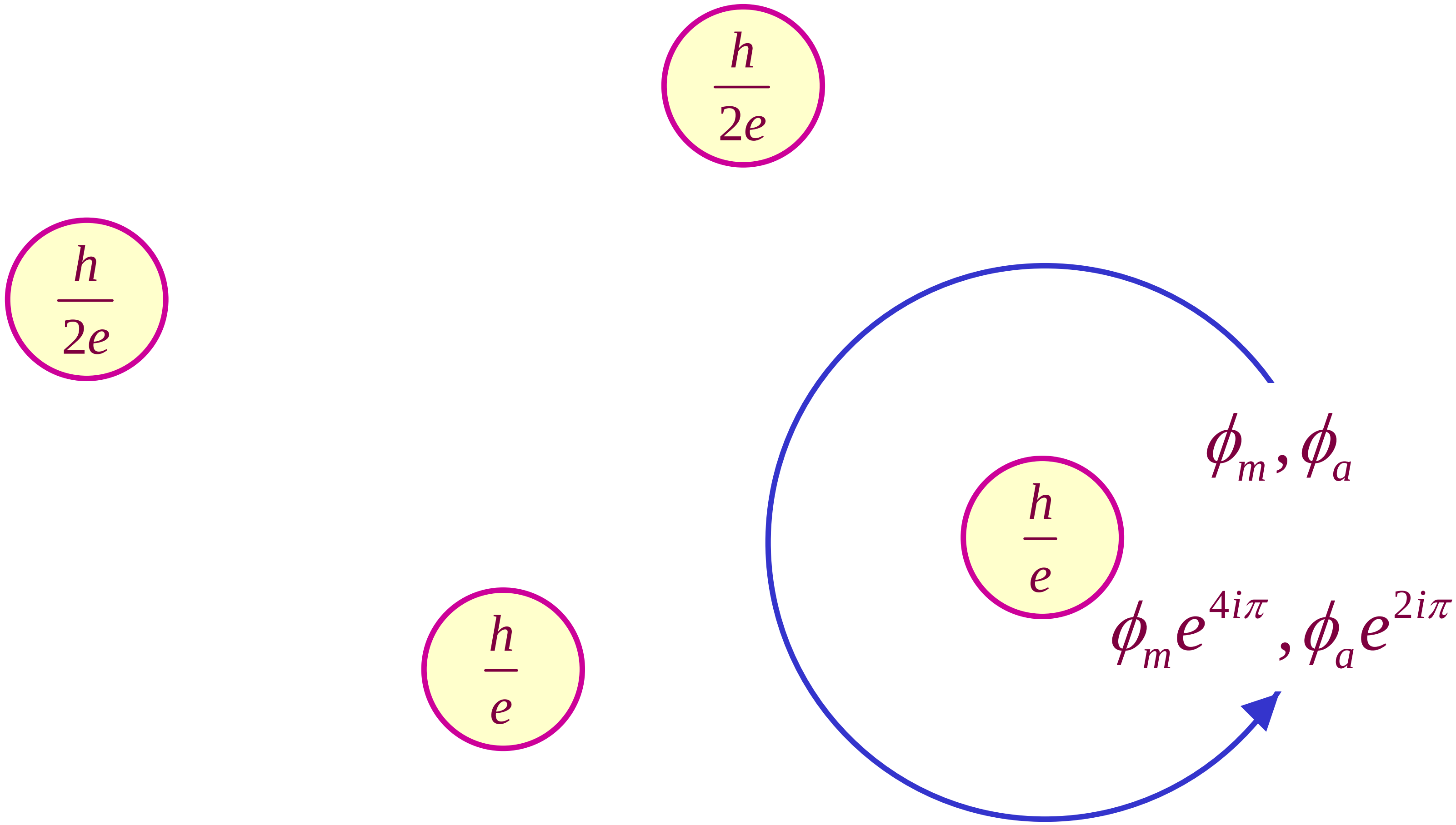

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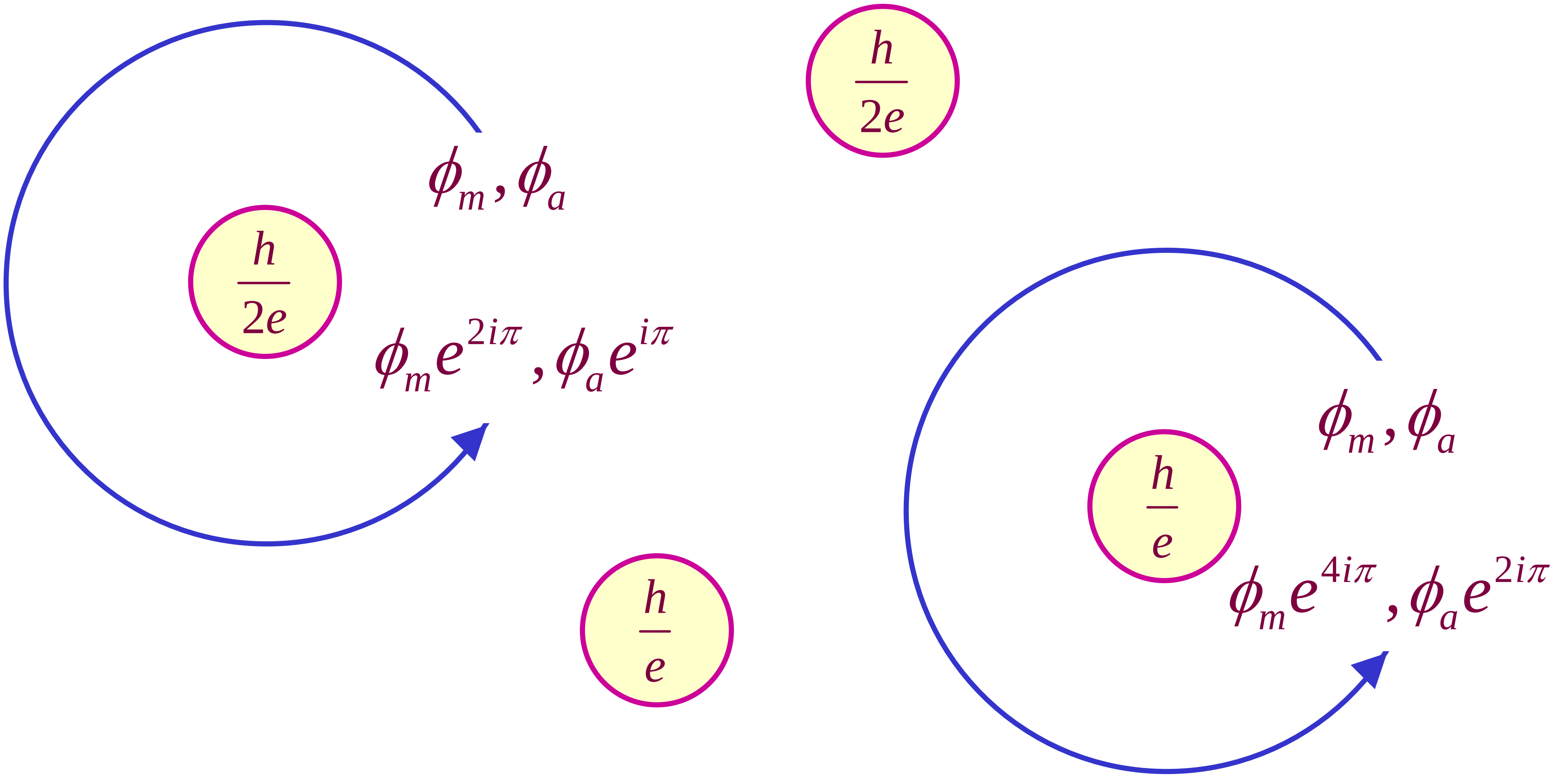
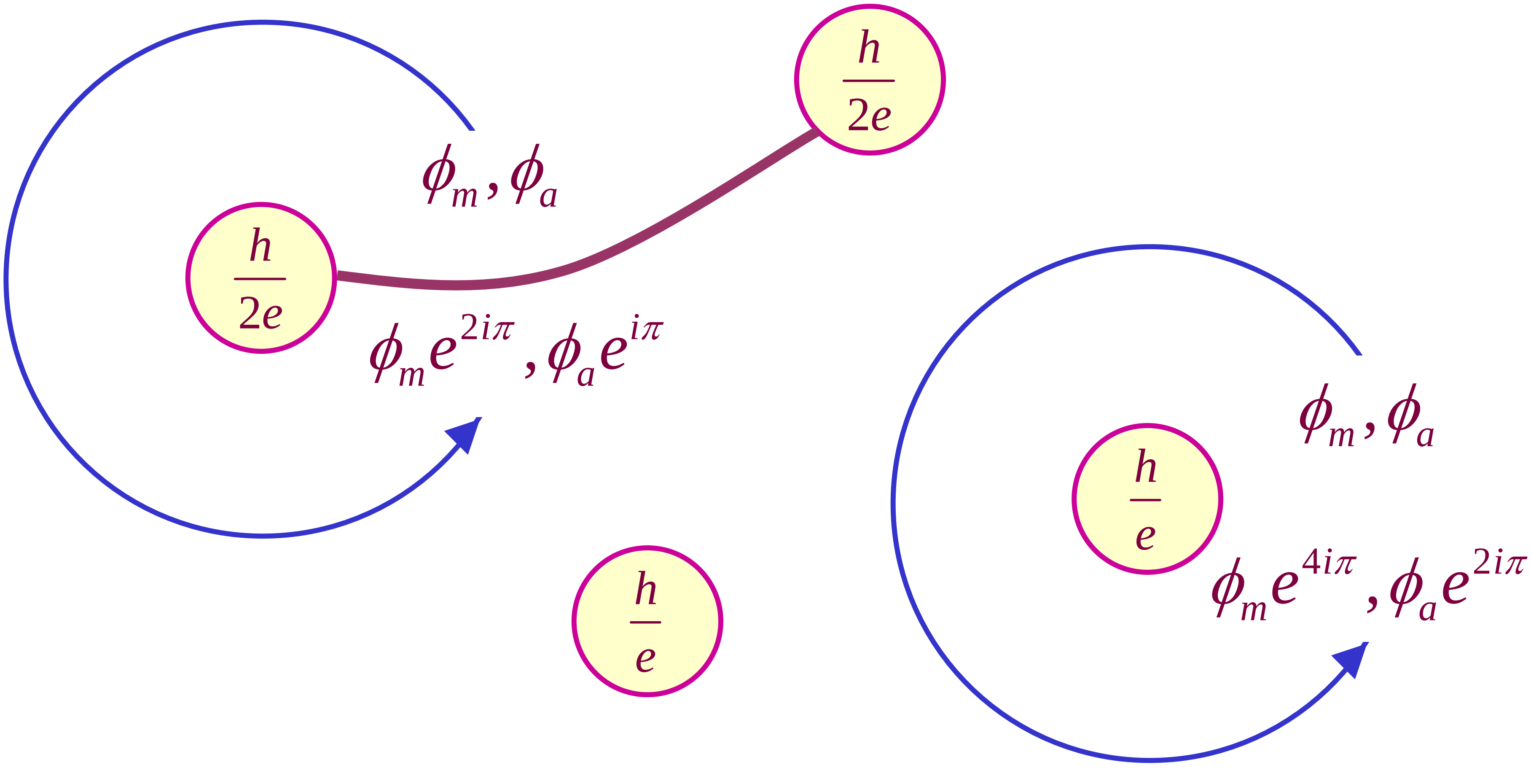


Vortices in an atomic superfluid

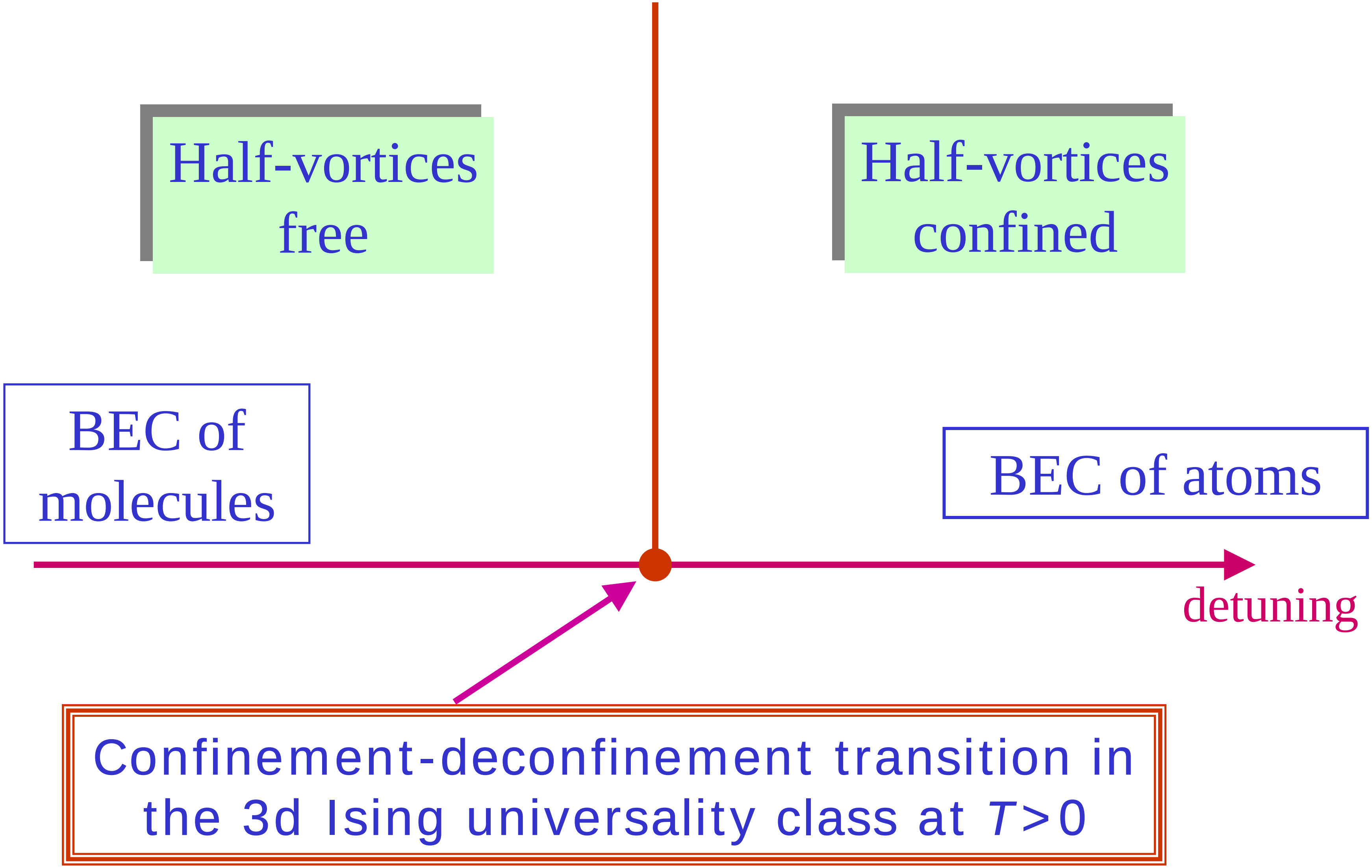
Why are the two superfluids distinct ?

Half vortices are confined in pairs by a ``branch cut''
which costs a finite energy per unit length



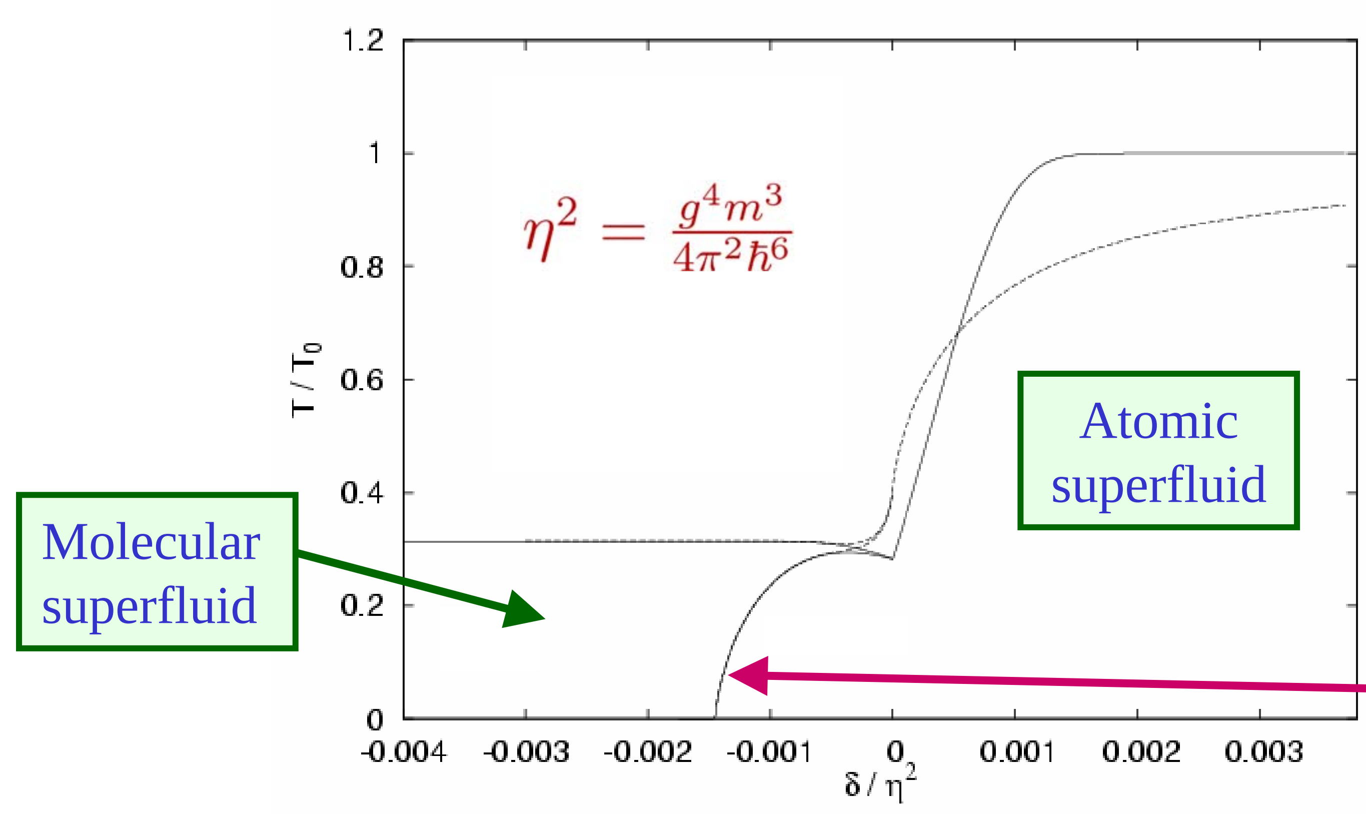
Vortices in an atomic superfluid

Bose gas near a Feshbach resonance



Bose gas near a Feshbach resonance

$$
\begin{aligned}
H &= \int dx \psi_{\mathrm{m}}^{\dagger}(x)\left[-\frac{\hbar^2\nabla^2}{4m}+\delta-2\mu\right]\psi_{\mathrm{m}}(x)+\int dx\psi_{\mathrm{a}}^{\dagger}(x)\left[-\frac{\hbar^2\nabla^2}{2m}-\mu+\frac{T_{\mathrm{bg}}}{2}\psi_{\mathrm{a}}^{\dagger}(x)\psi_{\mathrm{a}}(x)\right]\psi_{\mathrm{a}}(x)\\
&+ \int dx g\left[\psi_{\mathrm{m}}^{\dagger}(x)\psi_{\mathrm{a}}(x)\psi_{\mathrm{a}}(x)+\psi_{\mathrm{a}}^{\dagger}(x)\psi_{\mathrm{a}}^{\dagger}(x)\psi_{\mathrm{m}}(x)\right]\\
&+ \int dx\frac{T_{\mathrm{mm}}}{2}\psi_{\mathrm{m}}^{\dagger}(x)\psi_{\mathrm{m}}^{\dagger}(x)\psi_{\mathrm{m}}(x)\psi_{\mathrm{m}}(x)+\int dx T_{\mathrm{am}}\psi_{\mathrm{m}}^{\dagger}(x)\psi_{\mathrm{a}}^{\dagger}(x)\psi_{\mathrm{a}}(x)\psi_{\mathrm{m}}(x)
\end{aligned}
$$



Note: transition occurs at *negative* detuning

Bose gas near a Feshbach resonance

Detecting the Ising transition:

• Observation of vortices

• Non-analytic increase in atomic density

• "Critical slowing down" : strong damping of collective modes and decay of atomic density fluctuations into critical fluctuations