Collective modes of a soliton train in a Fermi superfluid

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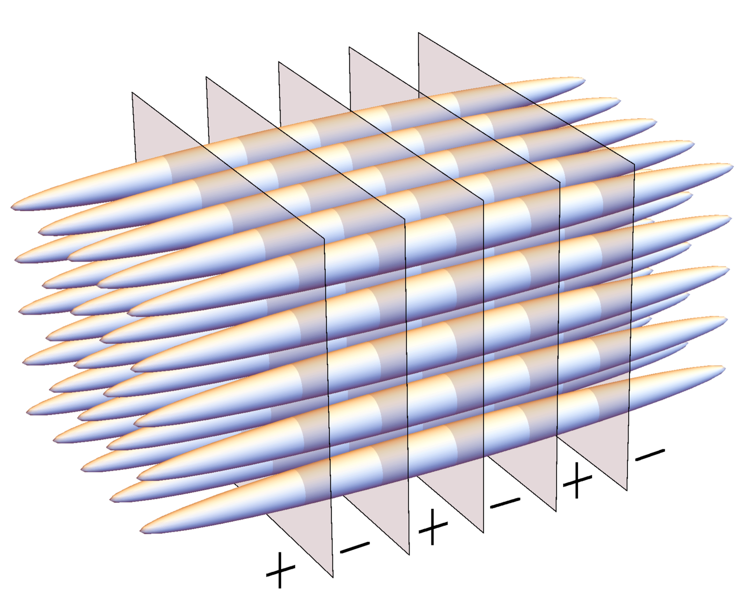
I. Summary

- Investigated collective modes of a soliton train in a quasi-1D Fermi superfluid
- Found novel modes describing soliton-core oscillations
- Found dynamical instabilities — stabilized by imbalance
- Propose a way to directly engineer long-lived FFLO by phase imprinting + RF sweep

II. Proposed experimental set-up

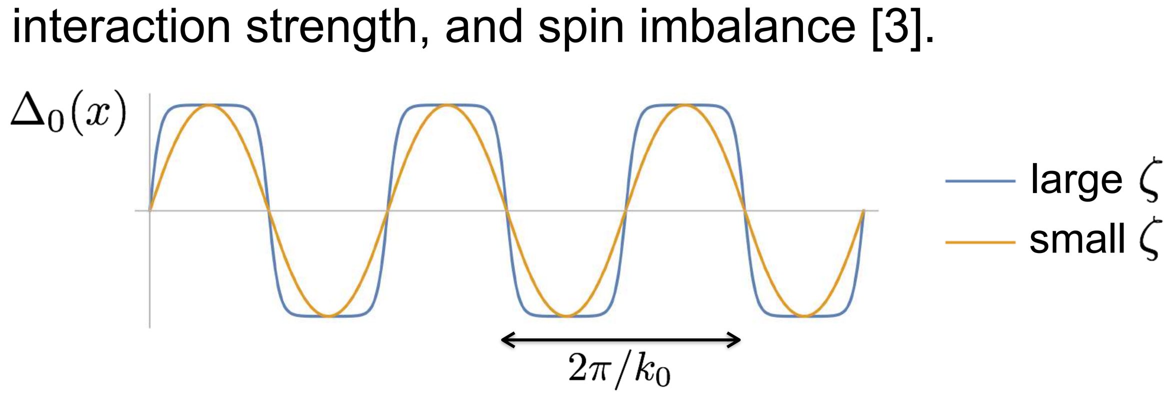


1. Create Fermi superfluid in array of tubes (no snake instability, long-range order [1]).
2. Phase imprint [2] multiple solitons.
3. Study their collective motion.
4. RF pulse to polarize cores, if desired (see V).

III. Theoretical Modeling

Stationary solution:

$\Delta_0(x) \propto \mathrm{sn}(x, \zeta)$, where ζ is set by the soliton spacing, interaction strength, and spin imbalance [3].



Finding collective modes:

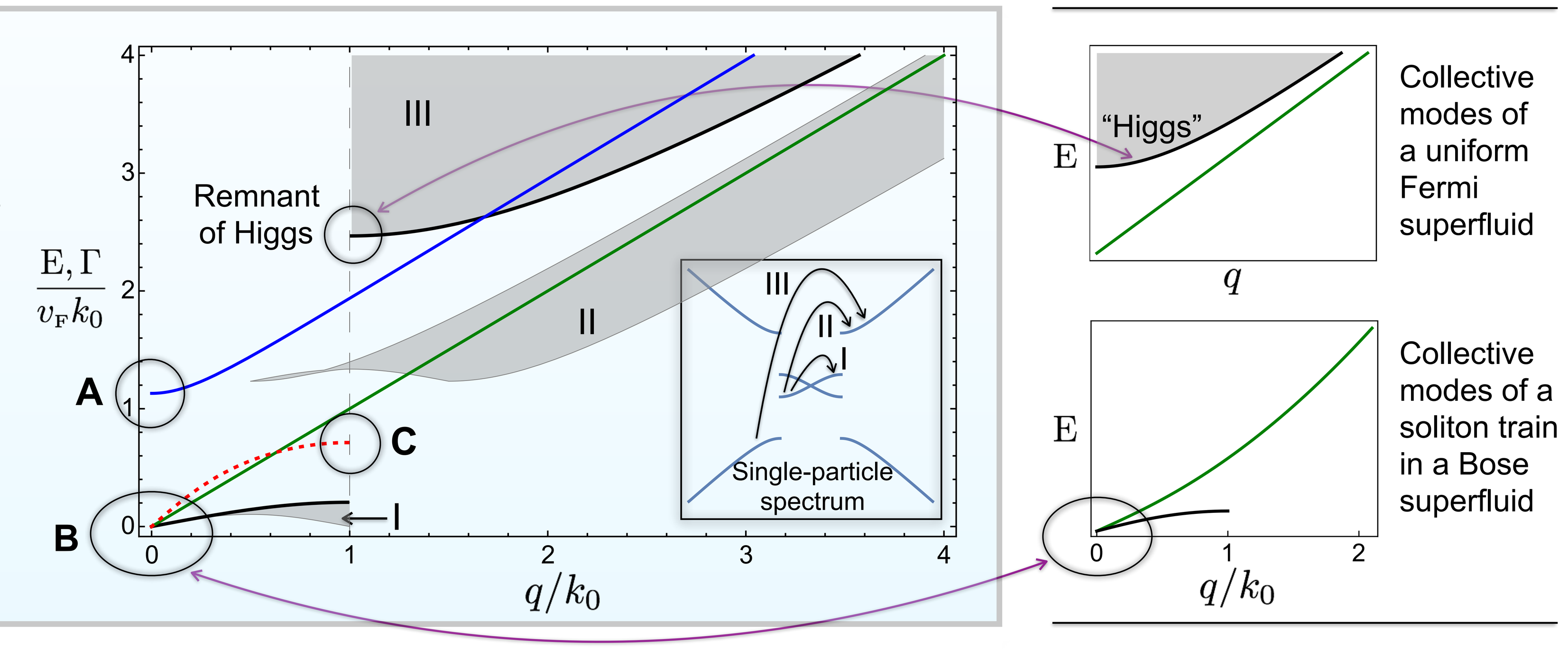
- Self-consistent Bogoliubov de-Gennes (BdG) formalism
- Extract collective modes from linearized dynamics of fluctuations about stationary solution
- Characterized by three tunable parameters:
  (i) k_0/k_F: wave-vector of the train
  (ii) $k_F a_{1D}$: interaction strength
  (iii) n_s: unpaired fermions per soliton (spin imbalance)

IV. Results

1. Spectrum contains: two Goldstone modes, "Higgs" mode, novel gapped modes describing oscillations of soliton cores, three disconnected continua, and a growing instability toward a uniform state.

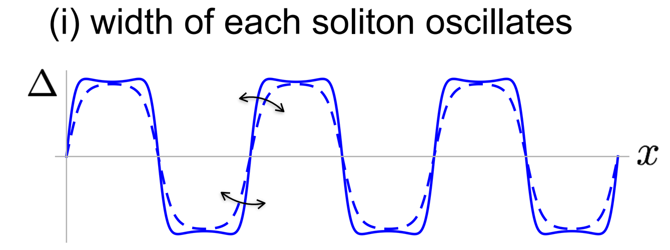
Collective mode spectrum of a soliton train without spin imbalance, for $k_0/k_F = 0.05$, $k_F a_{1D} = 2.6$.

Gray regions: particle-hole continua.
Solid curves: energy of stable modes.
Dotted curve: growth rate (Γ) of unstable mode.

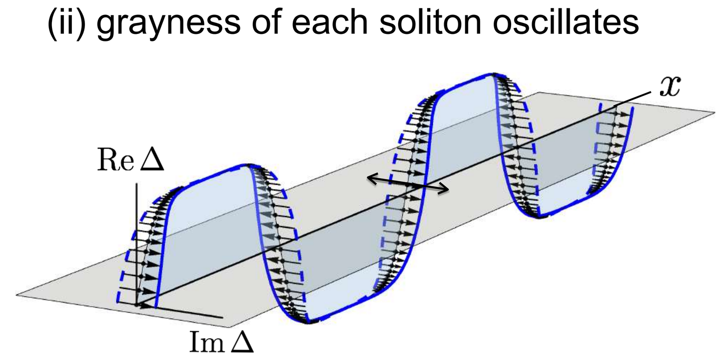


A. Two-fold degenerate "core" modes

(i) width of each soliton oscillates

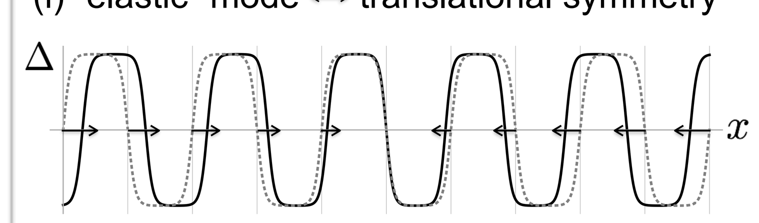


(ii) grayness of each soliton oscillates

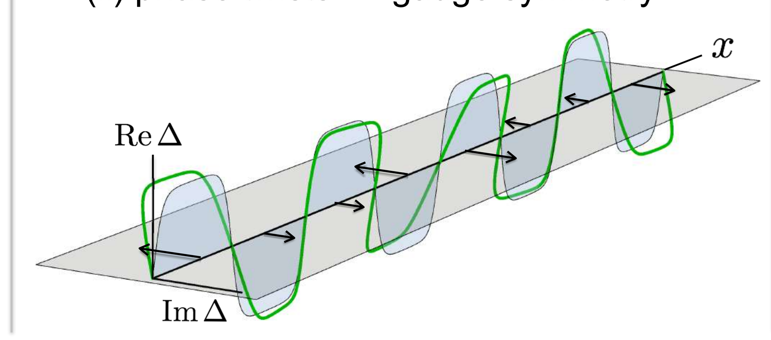


B. Two gapless Goldstone modes

(i) "elastic" mode ↔ translational symmetry

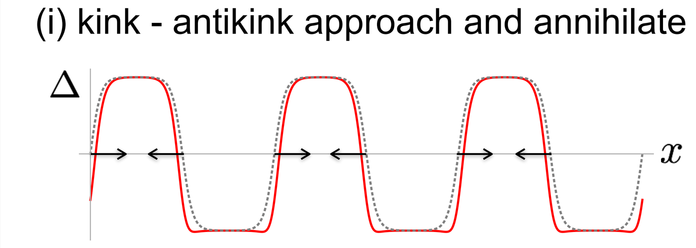


(ii) phase twists ↔ gauge symmetry

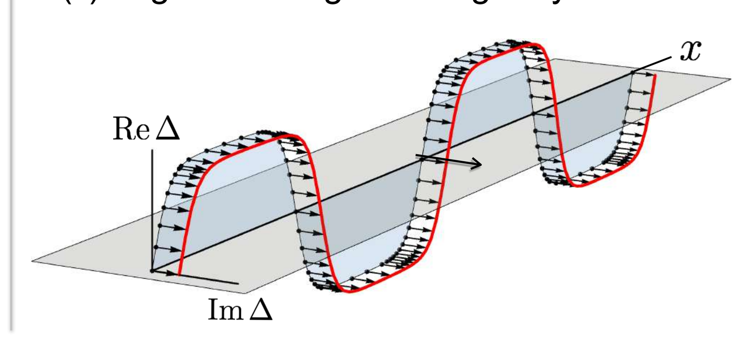


C. Two-fold degenerate unstable modes

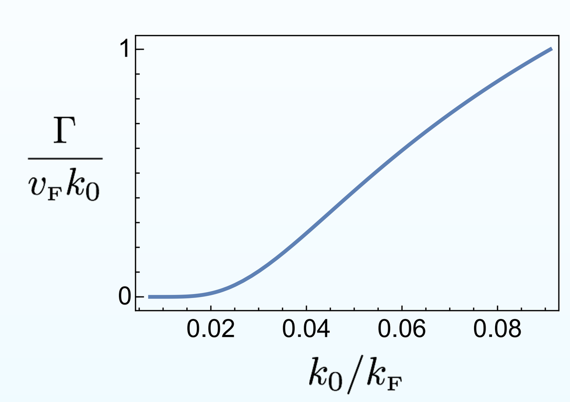
(i) kink - antikink approach and annihilate



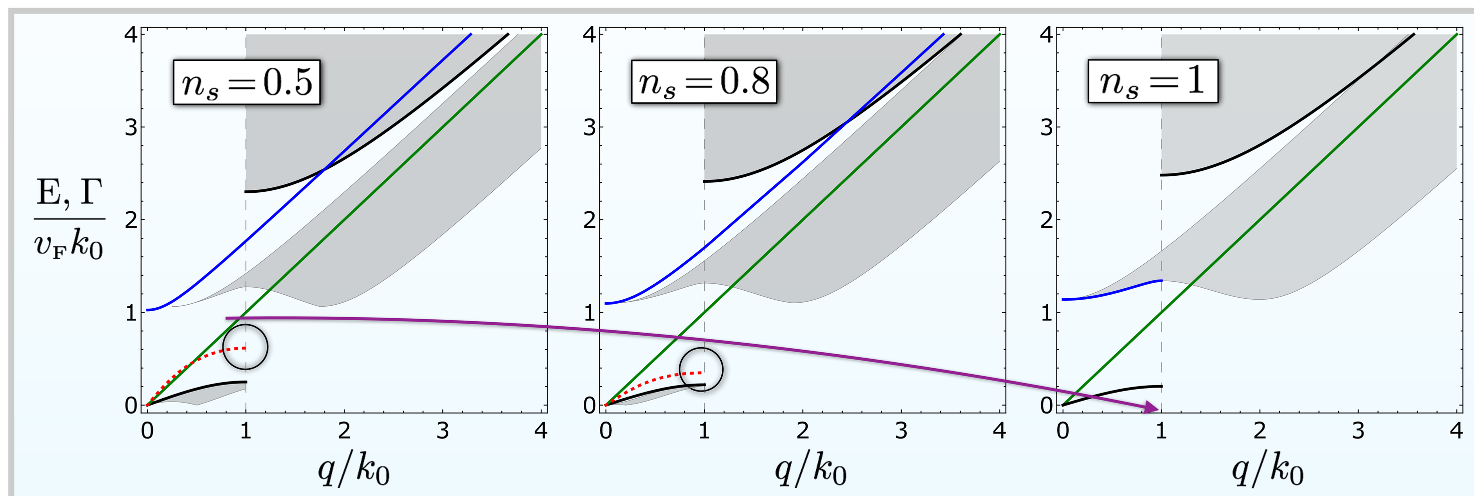
(ii) Δ grows along the imaginary axis



2. The train can be stabilized by creating solitons farther apart or filling them with unpaired fermions.



Instability rate vs inverse soliton spacing, for $k_F a_{1D} = 2.4$.



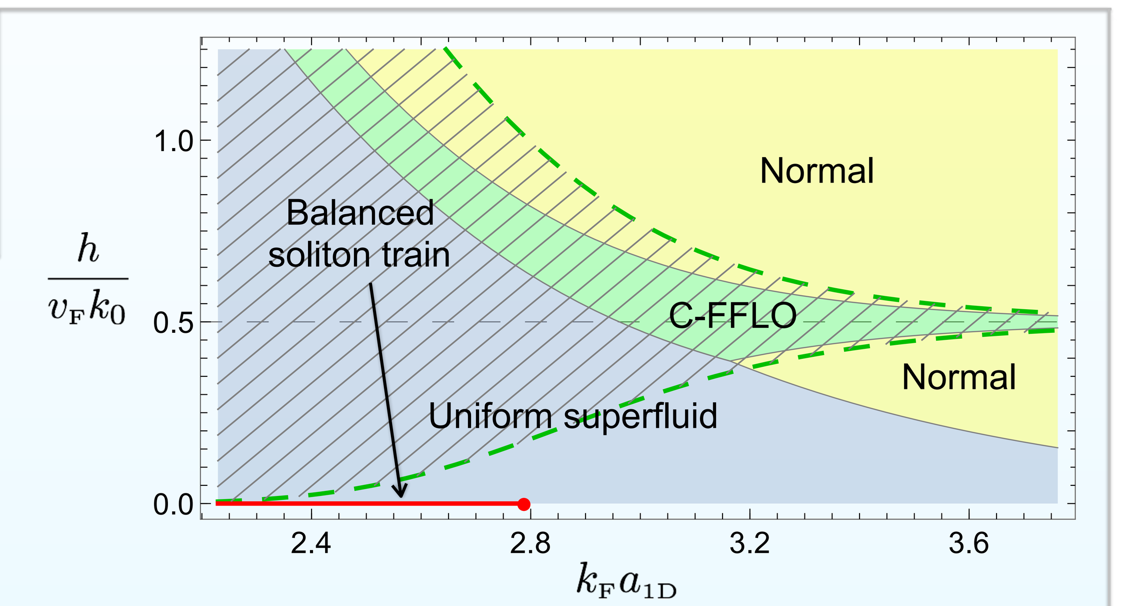
Variation with spin imbalance, for $k_0/k_F = 0.05$, $k_F a_{1D} = 2.65$.

3. The FFLO phase with one unpaired fermion per soliton (C-FFLO) is dynamically stable, even when it is not the ground state.

Phase diagram (with $k_0/k_F = 0.05$ for soliton trains).

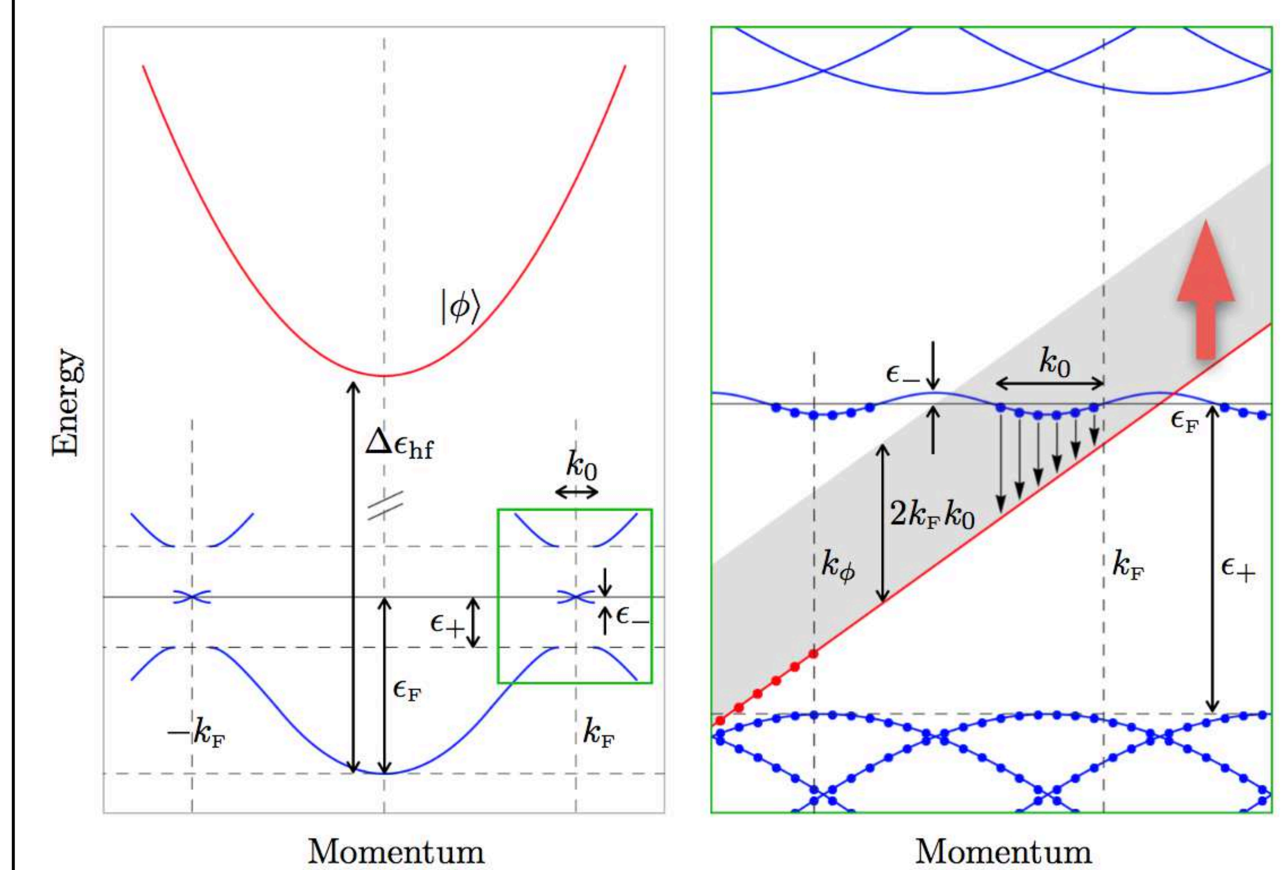
Solid regions show lowest energy states. C-FFLO is dynamically stable throughout the hatched region.

h: chemical potential difference.



V. Creating C-FFLO states

1. Create balanced soliton train by phase imprinting.
2. Apply radio waves which couple spin-↑ atoms to a third noninteracting spin state $|\phi\rangle$.
3. Sweep the frequency to break up pairs in soliton cores and convert the spin-↑ atoms into $|\phi\rangle$ atoms.



— Utilizes separation of energy scales between localized and bulk excitations

— Robust for strong interactions $[(k_0/k_F)\, e^{\pi k_F a_{1D}/2} \lesssim 0.6]$

VI. Conclusions

- Soliton train unstable: stabilized by increasing soliton spacing / interaction strength, or adding imbalance
- New modes: width/grayness oscillations of solitons
- Collective modes and instability can be probed using spectroscopic / imaging techniques [2,4,5]
- C-FFLO phase stable even when not ground state — engineer by phase imprinting and RF sweep

Also in 3D: imbalance stabilizes against snake instability [6]

1. Y. Liao et. al., Nature 467, 567 (2010)
2. M. J. H. Ku et. al., Phys Rev. Lett. 116, 045304 (2016)
3. K. Machida and H. Nakanishi, Phys. Rev. B 30, 122 (1984)
4. L. M. Aycock *et. al.*, PNAS 114, 2503 (2017)
5. M. Endres *et. al.*, Nature 487, 454 (2012)
6. M. Reichl and E. J. Mueller, Phys. Rev. A 95, 053637 (2017)