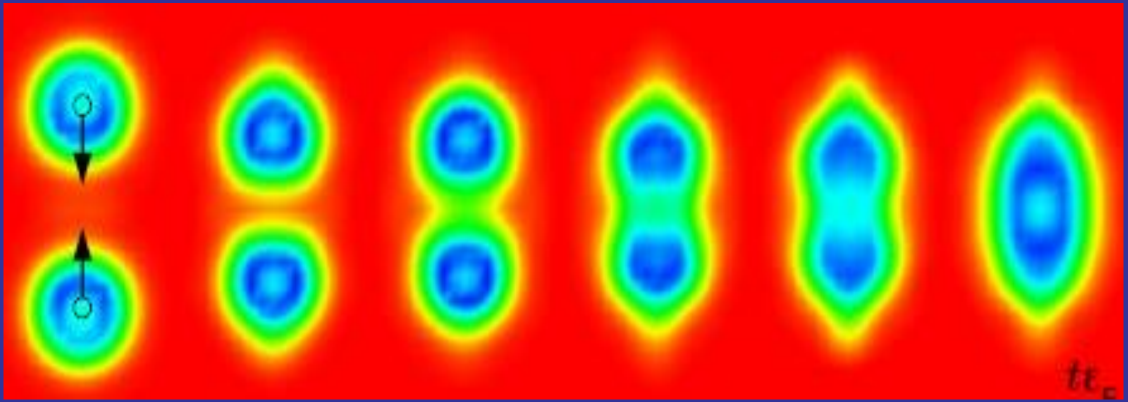
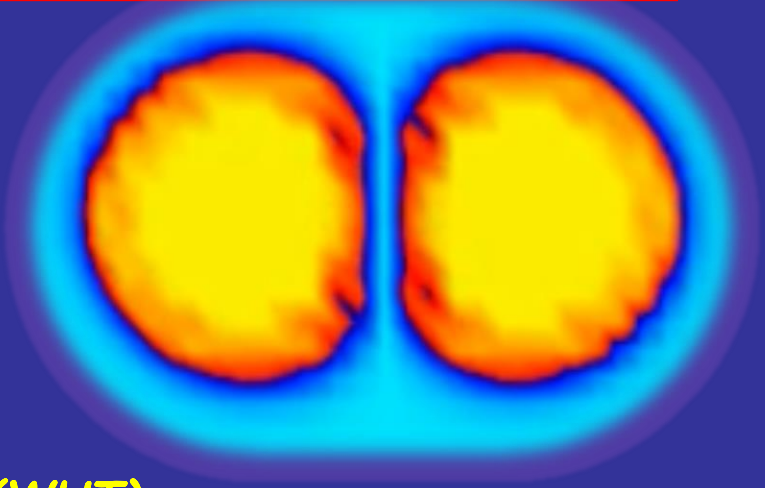
Solitonic excitations in heavy ion collision and spin imbalanced, ultracold atomic gases.





Piotr Magierski
Warsaw University of Technology (WUT)
University of Washington (UW)

Collaborators:

Matthew Barton (WUT)
Andrzej Makowski (WUT)
Kazuyuki Sekizawa (Tokyo Inst. of Techn.)
Buğra Tüzemen (WUT)
Gabriel Wlazłowski (WUT)
Tomasz Zawiślak (WUT)

CONNECTIONS BETWEEN COLD ATOMS AND NUCLEAR MATTER: FROM LOW TO HIGH ENERGIES.

06 June 2022 — 10 June 2022

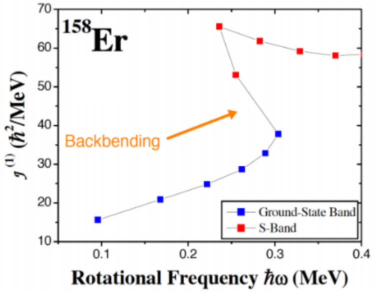
OUTLINE:

- Solitonic excitations in nuclear collisions and ultracold Fermi gases.
- Metastable Larkin-Ovchinnikov droplets (*ferrons*) in ultracold Fermi gas.

What do we know about pairing correlations in atomic nuclei?

Odd-even mass staggering gives us estimate of the pairing strength (unfortunately obscured by polarization effects)

$$|\Delta| \approx \frac{12}{\sqrt{A}}\ \text{MeV}$$

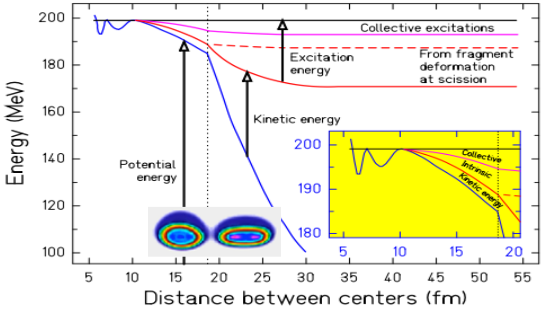


High spin experimental data: backbending of moments of inertia produced by the alignment of the correlated nucleon pair is a sensitive function of pairing correlations.

A. Johnson, H. Ryde, S.A. Hjorth,
Nucl. Phys. A179, 753 (1972)

Theoretical description of large amplitude nuclear motion require to include pairing correlations,
e.g. Nuclear fission at low energies

A. Bulgac, P.M., K.J. Roche, I. Stetcu, Phys. Rev. Lett. 116, 122504 (2016)



From Schmidt & Jurado:Phys.Rev.C83:061601,2011

Can we probe the pairing field phase in nuclei?

Nuclear Josephson junction: enhancement of neutron pair transfer in nuclear collision

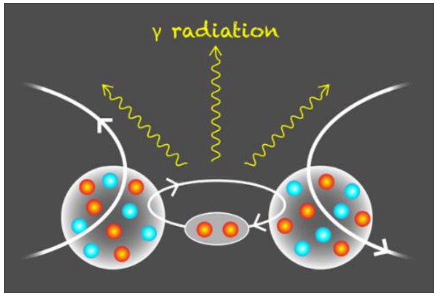
V.I. Gol'danskii, A.I. Larkin JETP 53, 1032 (1967)
K. Dietrich, Phys.Lett. B32, 428 (1970)

(Unfortunately experimental data are not conclusive)

Recent attempt: oscillatory pair transfer (AC Josephson junction)

C.Potel,F.Barranco,E.Vigezzi, R.A. Broglia, Phys.Rev. C103, L021601(2021)

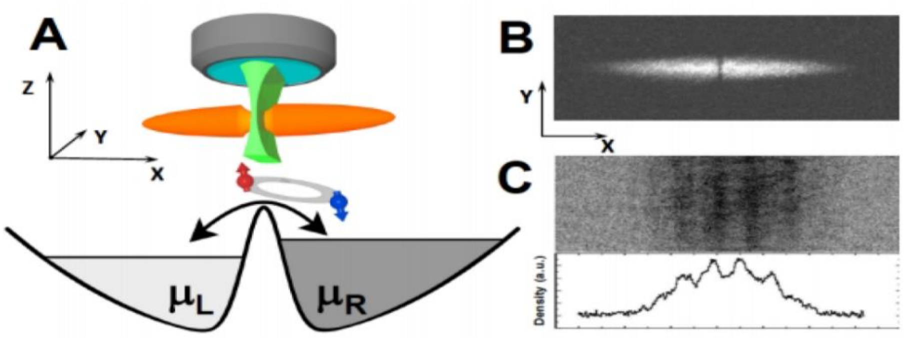
surprising agreement of gamma spectra with experiment!
(Although just one reaction: ^{116}Sn+ ^{60}Ni has been studied)

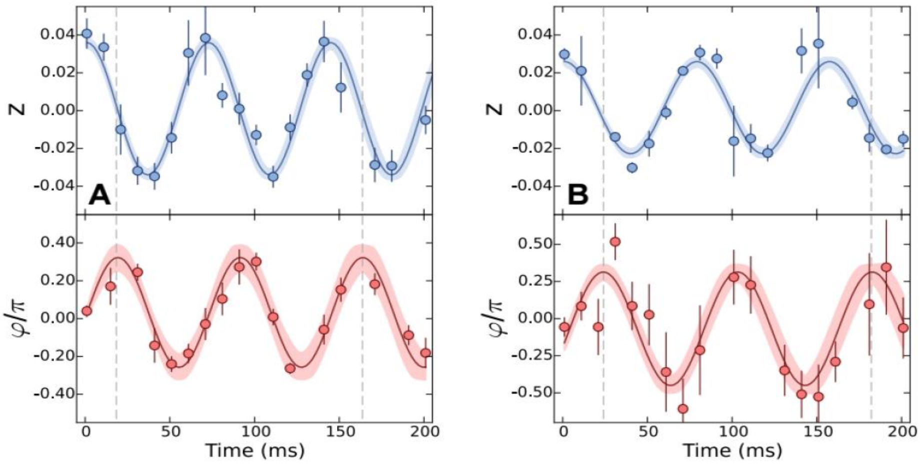


From P.M., Physics 14,27(2021)

Ultracold atomic gases: two regimes of pairing dynamics induced by phase difference

Weak coupling (weak link)



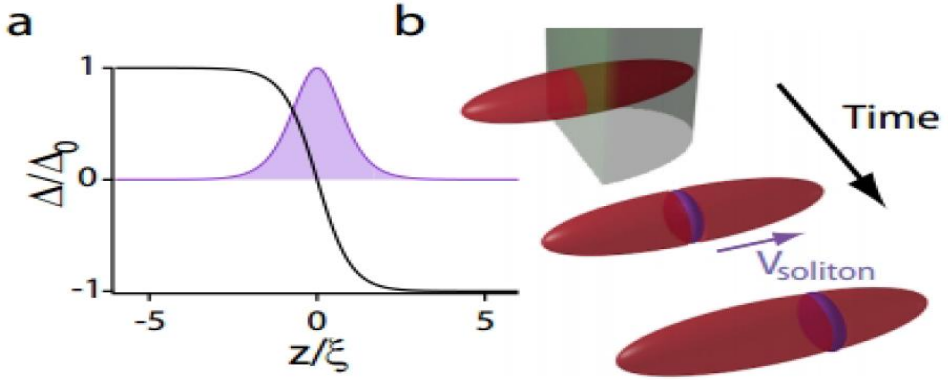


Observation of ***AC Josephson effect*** between two 6Li atomic clouds.

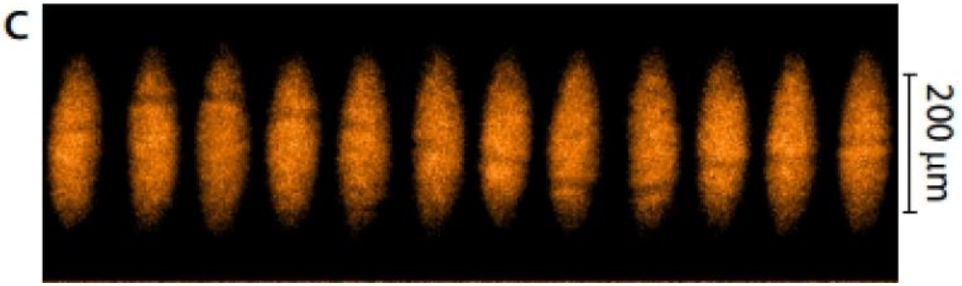
It need not to be accompanied by creation of a topological excitation.

G. Valtolina et al., Science 350, 1505 (2015).

Strong coupling



$$\Delta_L = \left|\Delta\right| e^{i\phi} \quad \Delta_R = \left|\Delta\right| e^{i(\phi+\pi)}$$



Creation of a „heavy soliton" after merging two superfluid atomic clouds.

MIT experiments: Nature 499, 426 (2013).
PRL 113, 065301 (2014); PRL 116, 045304 (2016);

Decay pattern:

dark soliton-> Phi soliton -> vortex ring -> vortex line

THEORY:

G. Wlazłowski, K. Sekizawa, M. Marchwiany, P. M., Phys. Rev. Lett. **120**, 253002 (2018)

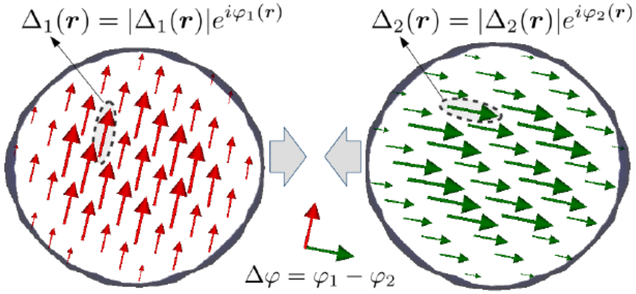
Nuclear collisions: strong coupling regime

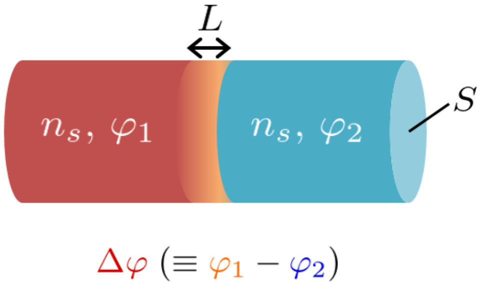
Collisions of superfluid nuclei having <u>different phases</u> of the <u>pairing fields</u>

<u>The main questions are:</u>

-how a possible solitonic structure can be manifested in nuclear system?
-what observable effect it may have on heavy ion reaction:
kinetic energy distribution of fragments, capture cross section, etc.?

Clearly, we cannot control phases of the pairing field in nuclear experiments and the possible signal need to be extracted after averaging over the phase difference.





From Ginzburg-Landau (G-L) approach:

$$\boxed{E_j = \frac{S}{L}\frac{\hbar^2}{2m} n_s \sin^2\frac{\Delta\varphi}{2}}$$

For typical values characteristic for two medium nuclei: $E_j \approx 30MeV$

Solving time-dependent problem for superfluids...

The real-time dynamics is given by equations, which are formally equivalent to the Time-Dependent HFB (TDHFB) or Time-Dependent Bogolubov-de Gennes (TDBdG) equations

$$h \sim f_1(n,\nu,\ldots)\boldsymbol{\nabla}^2 + \boldsymbol{f}_2(n,\nu,\ldots)\cdot\boldsymbol{\nabla} + f_3(n,\nu,\ldots)$$

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} u_{n,a}(\boldsymbol{r},t)\\ u_{n,b}(\boldsymbol{r},t)\\ v_{n,a}(\boldsymbol{r},t)\\ v_{n,b}(\boldsymbol{r},t)\end{pmatrix} = \begin{pmatrix} h_a(\boldsymbol{r},t) & 0 & 0 & \Delta(\boldsymbol{r},t)\\ 0 & h_b(\boldsymbol{r},t) & -\Delta(\boldsymbol{r},t) & 0\\ 0 & -\Delta^*(\boldsymbol{r},t) & -h_a^*(\boldsymbol{r},t) & 0\\ \Delta^*(\boldsymbol{r},t) & 0 & 0 & -h_b^*(\boldsymbol{r},t)\end{pmatrix}\begin{pmatrix} u_{n,a}(\boldsymbol{r},t)\\ u_{n,b}(\boldsymbol{r},t)\\ v_{n,a}(\boldsymbol{r},t)\\ v_{n,b}(\boldsymbol{r},t)\end{pmatrix}$$

We explicitly track fermionic degrees of freedom!

where *h* and Δ depends on "densities":

$$n_\sigma(\boldsymbol{r},t) = \sum_{E_n<E_c} |v_{n,\sigma}(\boldsymbol{r},t)|^2, \qquad \tau_\sigma(\boldsymbol{r},t) = \sum_{E_n<E_c} |\nabla v_{n,\sigma}(\boldsymbol{r},t)|^2,$$

$$\chi_c(\boldsymbol{r},t) = \sum_{E_n<E_c} u_{n,\uparrow}(\boldsymbol{r},t)v^*_{n,\downarrow}(\boldsymbol{r},t), \qquad \boldsymbol{j}_\sigma(\boldsymbol{r},t) = \sum_{E_n<E_c} \mathrm{Im}[v^*_{n,\sigma}(\boldsymbol{r},t)\nabla v_{n,\sigma}(\boldsymbol{r},t)],$$

$$\begin{aligned}\Delta(\mathbf{r}) &= g_{eff}(\mathbf{r})\chi_c(\mathbf{r})\\ \frac{1}{g_{eff}(\mathbf{r})} &= \frac{1}{g(\mathbf{r})} - \frac{mk_c(\mathbf{r})}{2\pi^2\hbar^2}\left(1 - \frac{k_F(\mathbf{r})}{2k_c(\mathbf{r})}\ln\frac{k_c(\mathbf{r})+k_F(\mathbf{r})}{k_c(\mathbf{r})-k_F(\mathbf{r})}\right)\end{aligned}$$

A. Bulgac, Y. Yu, Phys. Rev. Lett. 88 (2002) 042504
A. Bulgac, Phys. Rev. C65 (2002) 051305

huge number of nonlinear coupled 3D Partial Differential Equations
(in practice n=1,2,…, 10^5 - 10^6)

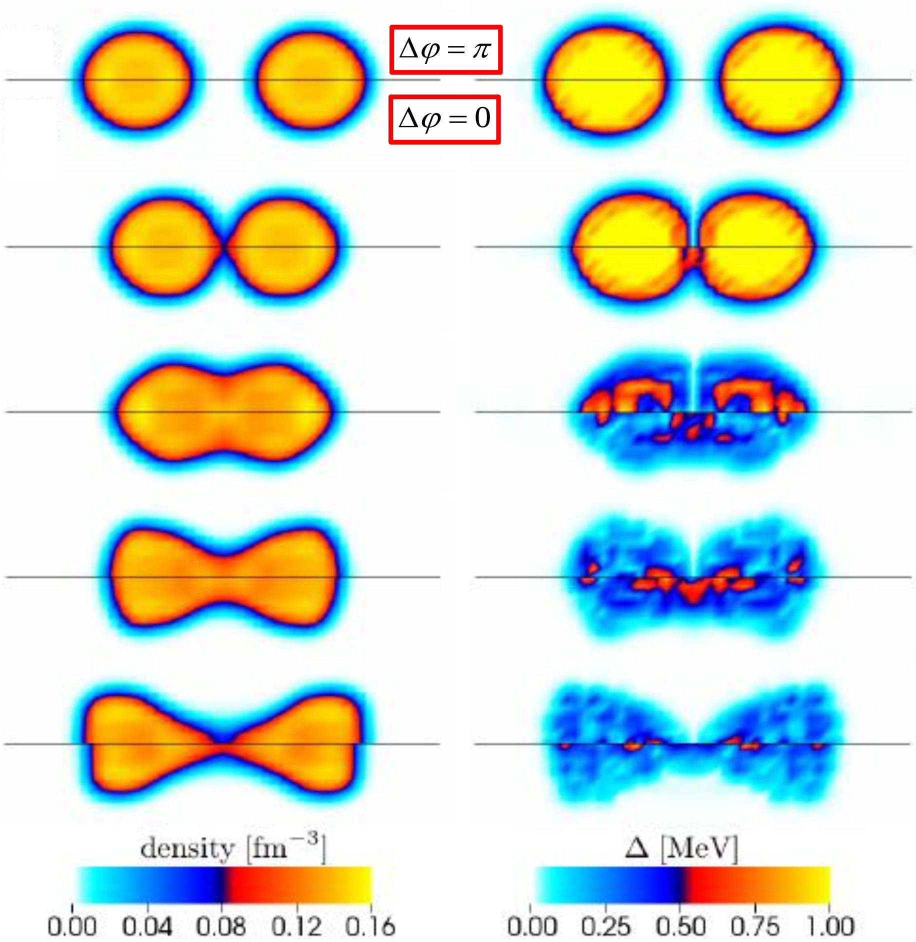
- P. M., *Nuclear Reactions and Superfluid Time Dependent Density Functional Theory*, Frontiers in Nuclear and Particle Physics, vol. 2, 57 (2019)
- A. Bulgac, *Time-Dependent Density Functional Theory and Real-Time Dynamics of Fermi Superfluids*, Ann. Rev. Nucl. Part. Sci. 63, 97 (2013)
- A. Bulgac, M.M. Forbes, P. M., Lecture Notes in Physics, Vol. 836, Chap. 9, p.305-373 (2012)

Present computing capabilities:

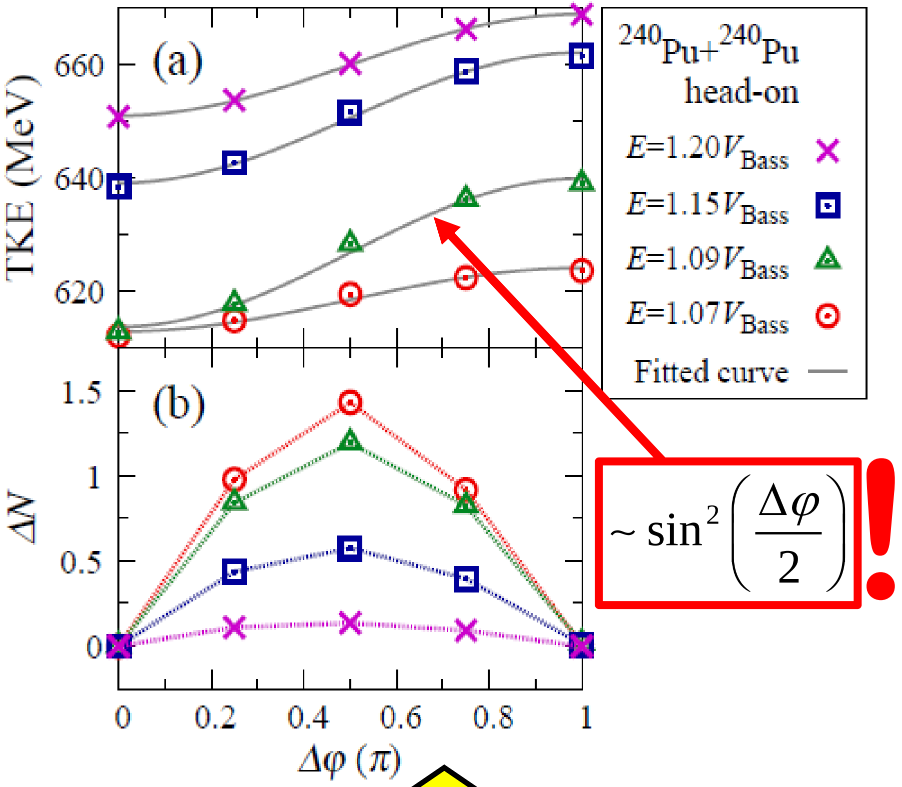
- full 3D (unconstrained) superfluid dynamics
- spatial mesh up to 100^3
- max. number of particles of the order of 10^4
- up to 10^6 time steps

(for cold atomic systems – time scale: a few ms
for nuclei – time scale: 100 zs)

^{240}Pu+^{240}Pu



Total kinetic energy of the fragments (TKE)



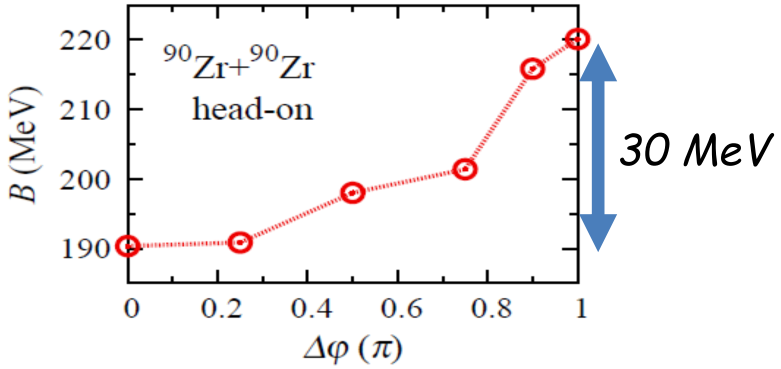
$$\sim \sin^2\left(\frac{\Delta\varphi}{2}\right)$$!

Average particle transfer between fragments.

Creation of the solitonic structure between colliding nuclei prevents energy transfer to internal degrees of freedom and consequently enhances the kinetic energy of outgoing fragments.

Surprisingly, the gauge angle dependence from the G-L approach is perfectly well reproduced in the kinetic energies of outgoing fragments!

Effective barrier height for fusion as a function of the phase difference



Results with Fayans functional
(no spin-orbit term)

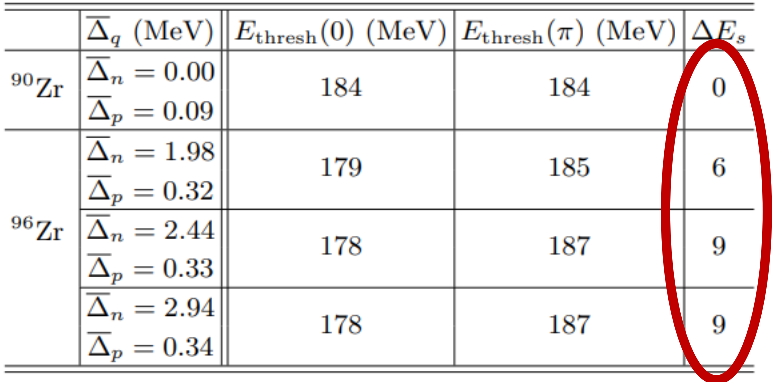
What is an average extra energy needed for the capture?

$$\boxed{E_{extra} = \frac{1}{\pi}\int_{0}^{\pi}\left(B\left(\Delta\varphi\right)-V_{Bass}\right)d\left(\Delta\varphi\right)\approx 10MeV}$$

The effect is found (within TDDFT) to be of the order of **30MeV** for medium nuclei and occur for energies up to 20-30% of the barrier height.

P. M., K. Sekizawa, G. Wlazłowski, Phys. Rev. Lett. 119 042501 (2017)

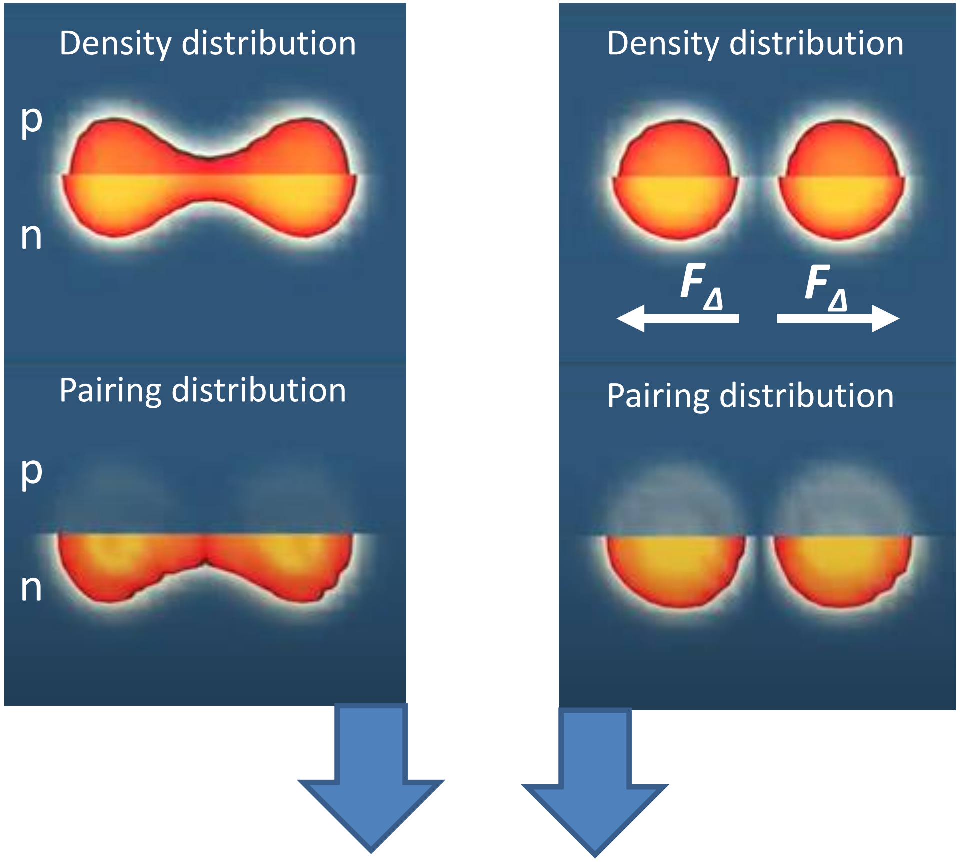
G. Scamps, Phys. Rev. C 97, 044611 (2018): **barrier fluctuations extracted from experimental Data indicate that the effect exists although is weaker than predicted by TDDFT**

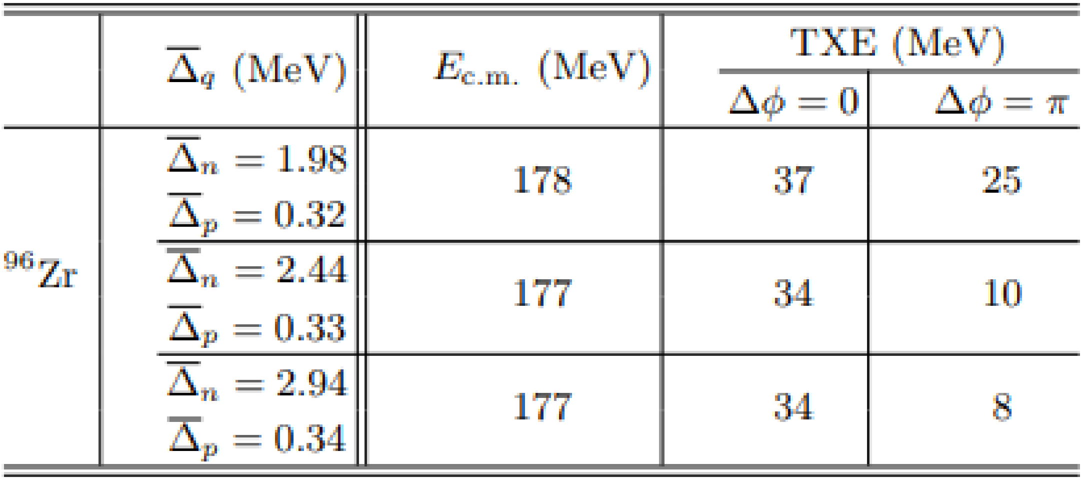


	Δ_q (MeV)	$E_{\text{thresh}}(0)$ (MeV)	$E_{\text{thresh}}(\pi)$ (MeV)	ΔE_s
^{90}Zr	$\Delta_n = 0.00$ $\Delta_p = 0.09$	184	184	0
^{96}Zr	$\Delta_n = 1.98$ $\Delta_p = 0.32$	179	185	6
	$\Delta_n = 2.44$ $\Delta_p = 0.33$	178	187	9
	$\Delta_n = 2.94$ $\Delta_p = 0.34$	178	187	9

Recent results with full SkM* functional:
Minimum energy needed for capture.

P.M., A. Makowski, M. Barton, K. Sekizawa, G. Wlazłowski,
Phys. Rev. C **105**, 064602 (2022)





	$\overline{\Delta}_q$ (MeV)	$E_{\text{c.m.}}$ (MeV)	TXE (MeV)	
			$\Delta\phi = 0$	$\Delta\phi = \pi$
^{96}Zr	$\overline{\Delta}_n = 1.98$ $\overline{\Delta}_p = 0.32$	178	37	25
	$\overline{\Delta}_n = 2.44$ $\overline{\Delta}_p = 0.33$	177	34	10
	$\overline{\Delta}_n = 2.94$ $\overline{\Delta}_p = 0.34$	177	34	8

Total excitation energy of the fragments

P.M., A. Makowski, M. Barton, K. Sekizawa, G. Wlazłowski, Phys. Rev. C **105**, 064602 (2022)

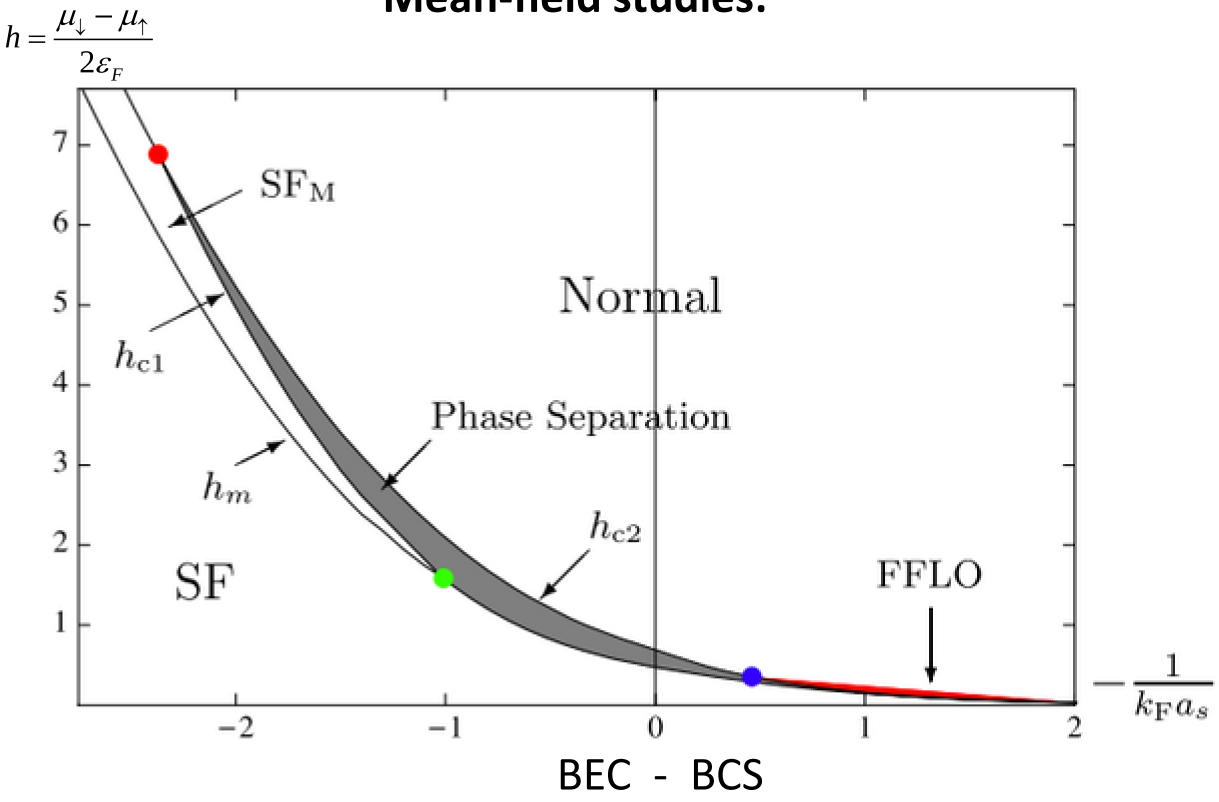
Inhomogeneous systems: Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase

Larkin-Ovchinnikov: $\Delta(r) \sim cos(qr)$

Fulde-Ferrell: $\Delta(r) \sim \exp(iqr)$

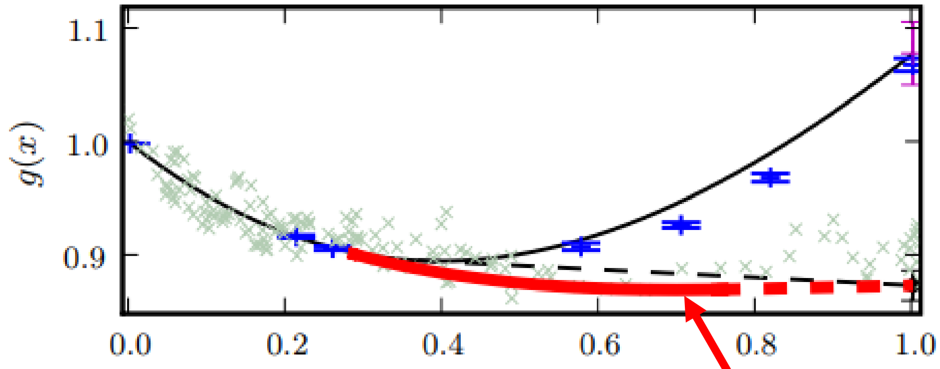
A.I. Larkin and Y. N. Ovchinnikov, Sov. Phys. JETP 20, 762 (1965)
P. Fulde and R. A. Ferrell, Phys. Rev. 135, A550 (1964)

Mean-field studies:

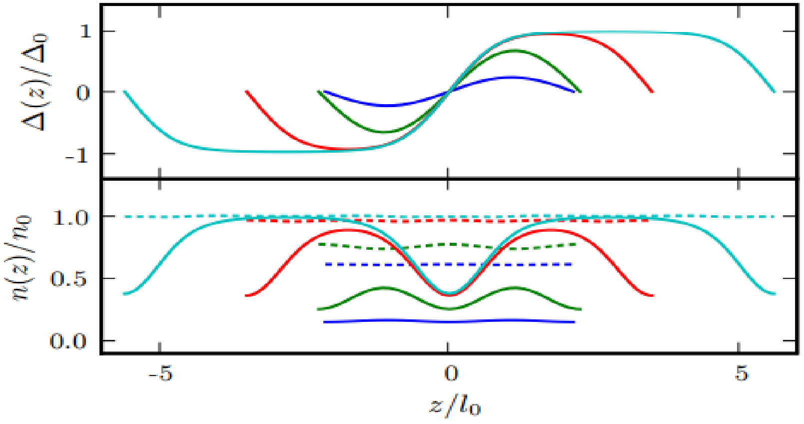


Radzihovsky,Sheehy, Rep.Prog. Phys.73,076501(2010)

Bulgac & Forbes have shown, within DFT, that Larkin-Ovchinnikov (LO) phase may exist in the unitary Fermi gas (UFG)



$E \sim [n_a g(x)]^{5/3}$



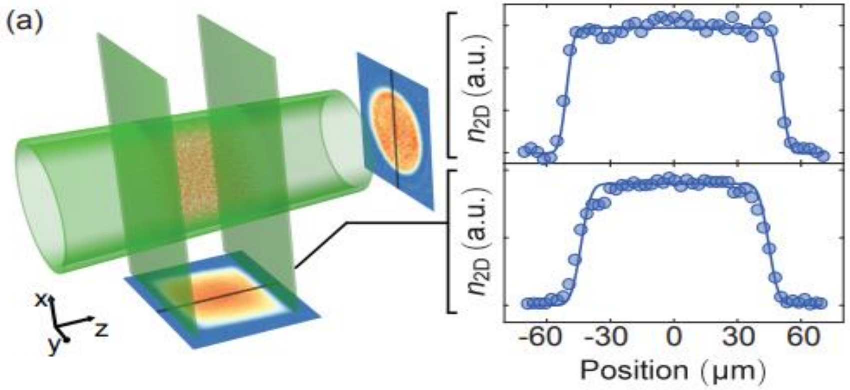
LO configuration – supersolid state

A. Bulgac, M.M.Forbes, PRL101,215301 (2008)

The problem:
In the trap the volume where LOFF phase may be created is relatively small .

unless

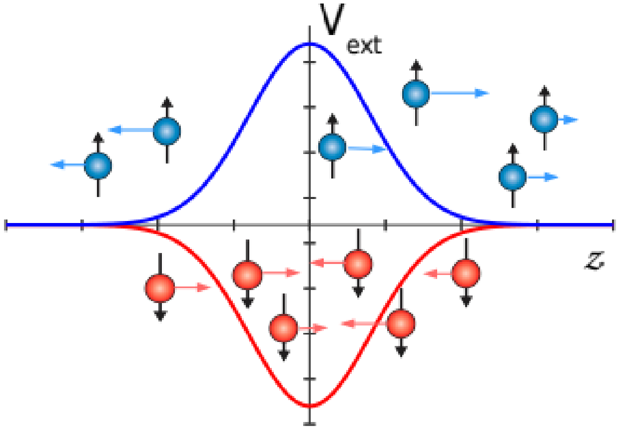
Ultracold atoms in a uniform potential



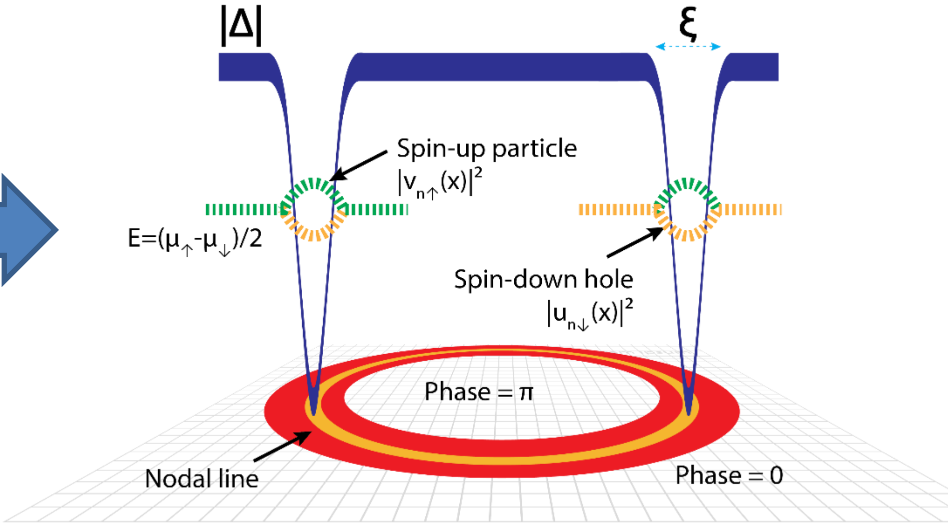
B. Mukherjee etal. Phys. Rev. Lett. 118, 123401 (2017)

Creating Larkin-Ovchinnikov droplet (ferron) dynamically in unitary Fermi gas

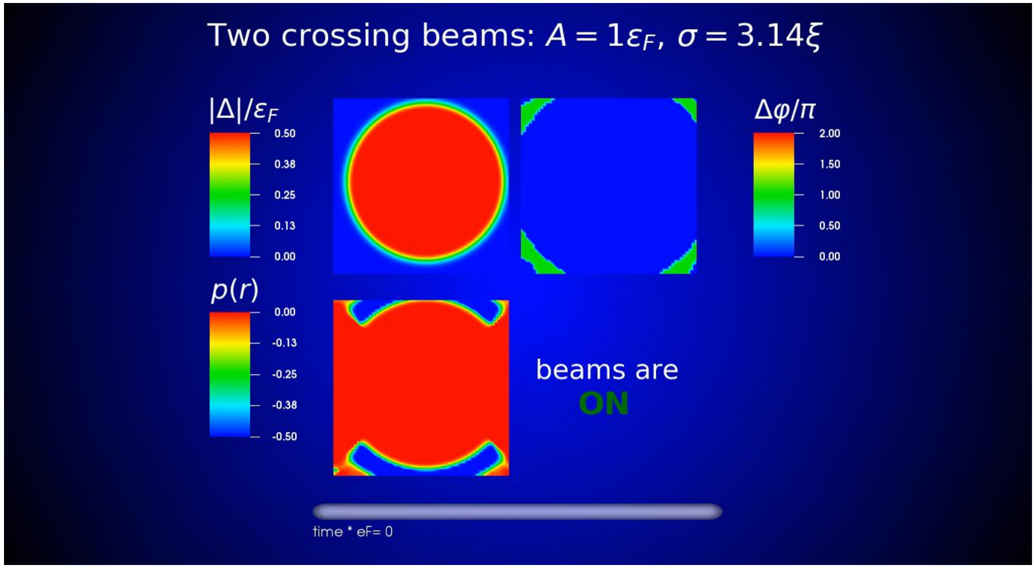
Spin-selective potential applied locally leads to Cooper pair breaking



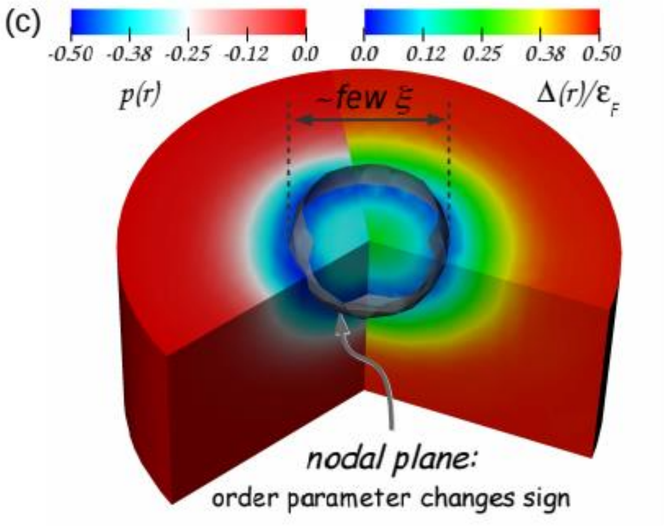
Pairing field nodal structure



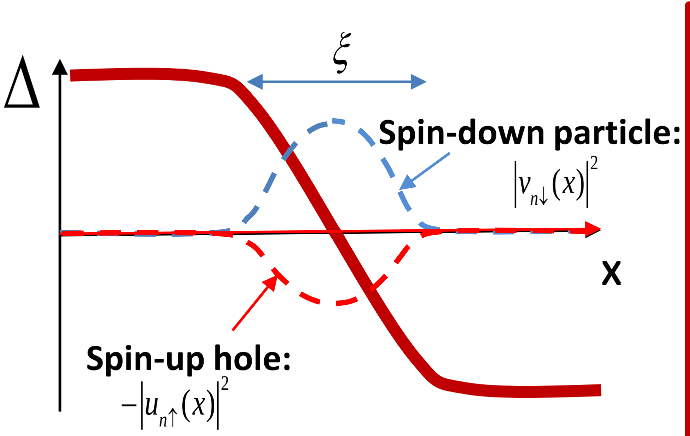
Generation of *ferron* in the unitary regime



Ferron structure



Andreev states and stability of pairing nodal points

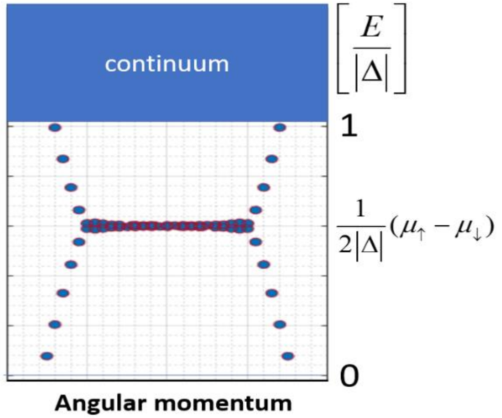


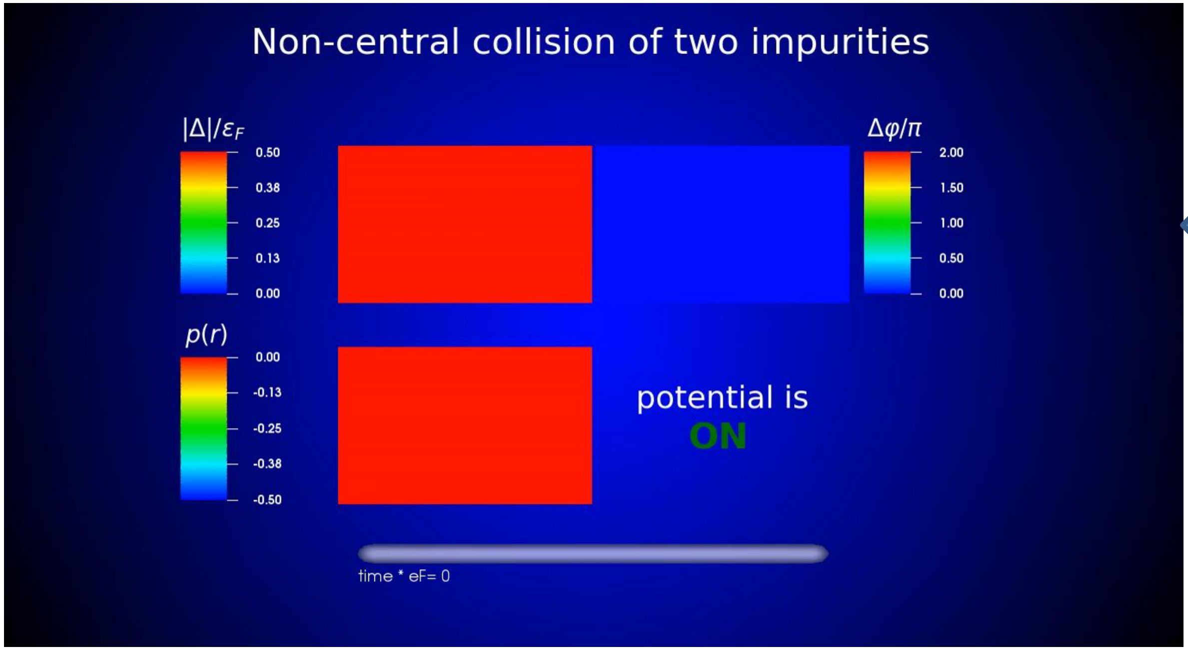
Due to quasiparticle scattering the localized Andreev states appear at the nodal point. These states induce local spin-polarization

BdG in the Andreev approx. ($\Delta \ll k_F^2$)

$$\begin{bmatrix} -2ik_F \dfrac{d}{dx} & \Delta(x) \\ \Delta^*(x) & 2ik_F \dfrac{d}{dx} \end{bmatrix} \begin{bmatrix} u_{n\uparrow}(x) \\ v_{n\downarrow}(x) \end{bmatrix} = E_n \begin{bmatrix} u_{n\uparrow}(x) \\ v_{n\downarrow}(x) \end{bmatrix}$$

Schematic spectrum of subgap states for ferron





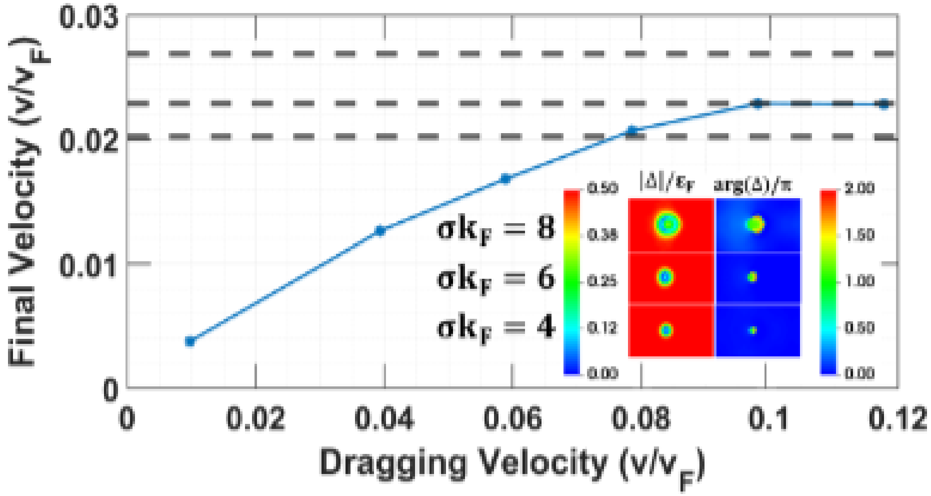
Surprisingly, the nodal structure remains stable even during collisions

P. M., B. Tüzemen, G. Wlazłowski, Phys. Rev. A100, 033613 (2019)

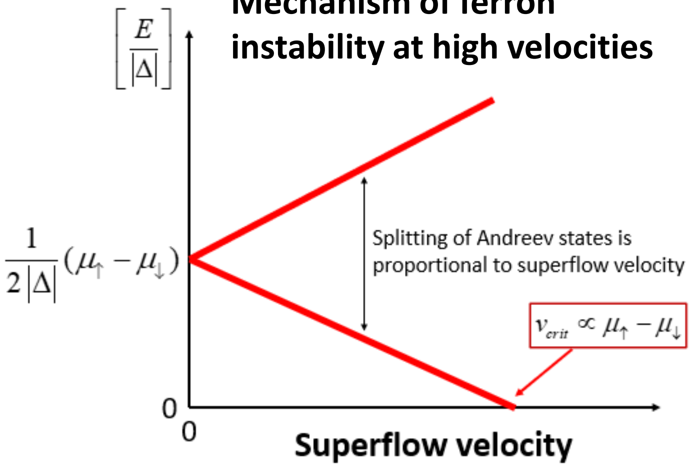
The velocities of impurites are about 30% of the velocity of sound.

Ferron critical velocity

Peculiarity of ferron dynamics: there is a limiting velocity propotional to its polarization.



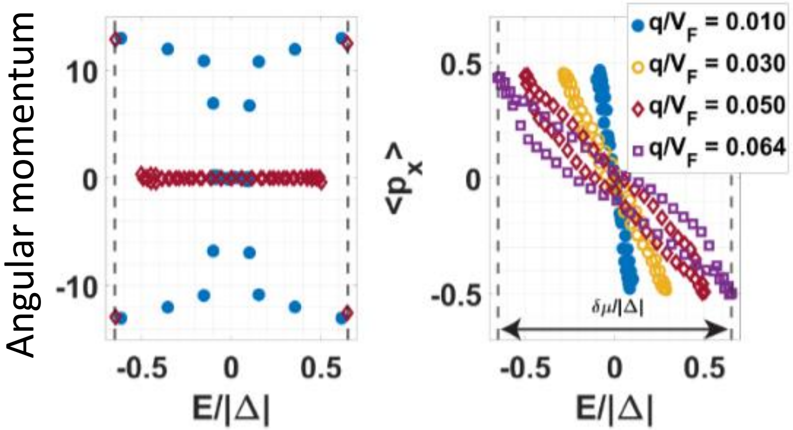
Mechanism of ferron instability at high velocities



Splitting of Andreev states is proportional to superflow velocity

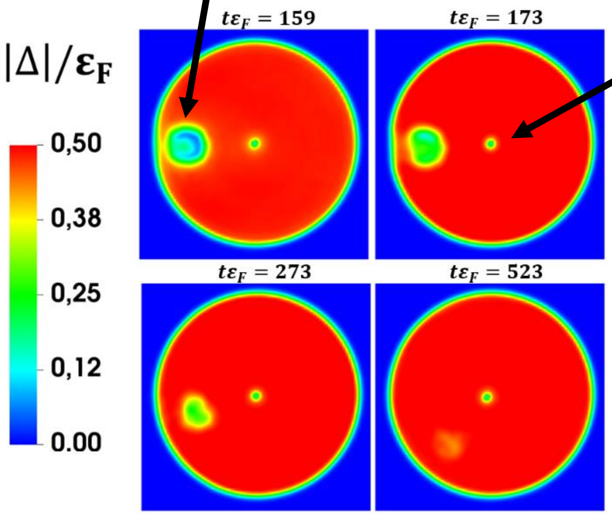
Andreev states for ferron

BdG calculations in 2D



Consequence:

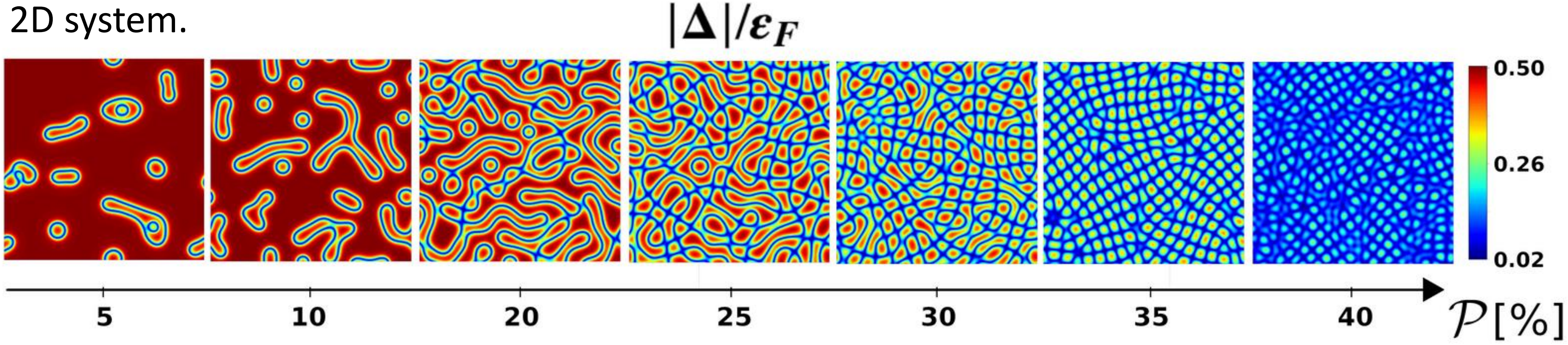
Instability of ***ferron*** in the vicinity of ***quantum vortex***



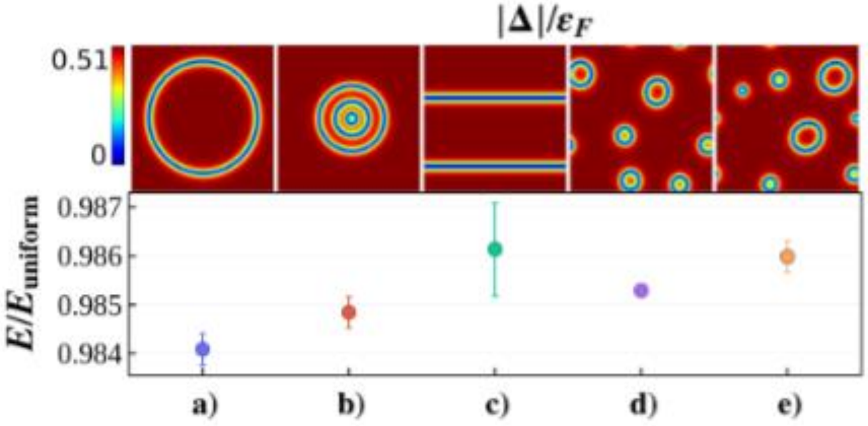
P. M., B. Tüzemen, G.Wlazłowski,
Phys. Rev. A 104, 033304 (2021)

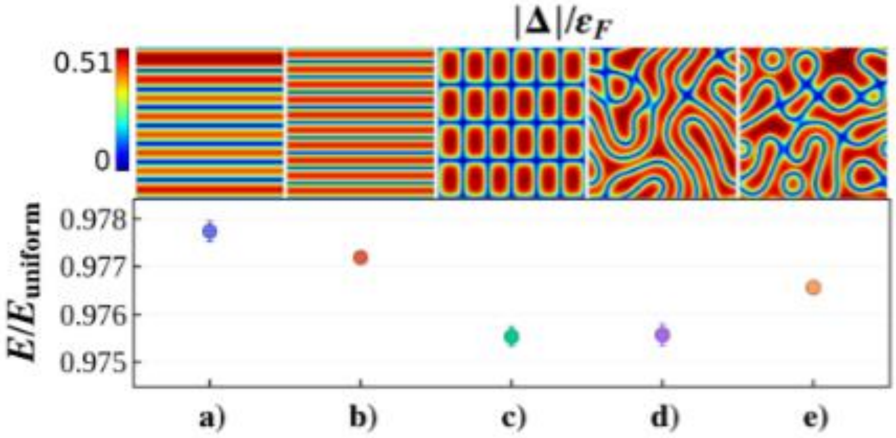
In search of LOFF phase: Supersolid or liquid crystal?

2D system.



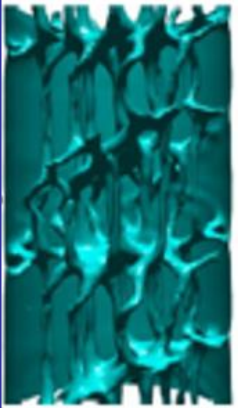
$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$





B. Tüzemen, T. Zawiślak, G. Wlazłowski, P.M. – in preparation

Nonequilibrium superfluidity in Fermi systems



Quantum turbulence

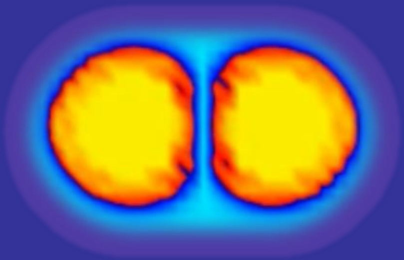
K. Hossain (WSU)
M.M. Forbes (WSU)
K. Kobuszewski (WUT)
S. Sarkar (WSU)
G. Wlazłowski (WUT)

K. Hossain et al.
Phys. Rev. A 105, 013304 (2022)

Vortex dynamics in neutron star crust

N. Chamel (ULB)
D. Pęcak (WUT)
G. Wlazłowski (WUT)

D. Pęcak et al.
Phys. Rev. C 104, 055801 (2021)



Nuclear collisions

M. Barton (WUT)
A. Boulet (WUT)
A. Makowski (WUT)
K. Sekizawa (Tokyo I.)
G. Wlazłowski (WUT)

P.M. et al. Phys. Rev. Lett 119 042501 (2017)
P.M. et al. Phys. Rev. C **105**, 064602 (2022)

Josephson junction in atomic Fermi gases - dissipative effects

N. Proukakis (NU)
M. Tylutki (WUT)
G. Wlazłowski (WUT)
K. Xhani (LENS & NU)

K. Xhani et al. (in preparation)

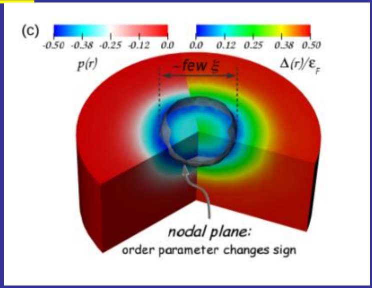
Collisions of vortex-antivortex pairs

A. Barresi (WUT)
A. Boulet (WUT)
G. Wlazłowski (WUT)
and LENS exp. Group

A. Boulet et al. arxiv:2201.07626
A. Barresi et al. (in preparation)

Spin-imbalanced Fermi gases

B. Tuzemen (WUT)
G. Wlazłowski (WUT)
T. Zawiślak (WUT)



P.M. et al. Phys. Rev. A100, 033613 (2019),
Phys. Rev. A104, 033304 (2021),
B. Tuzemen et al. (in preparation)