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Solitonic Excitations in Collisions of Superfluid Nuclei

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in collaboration with

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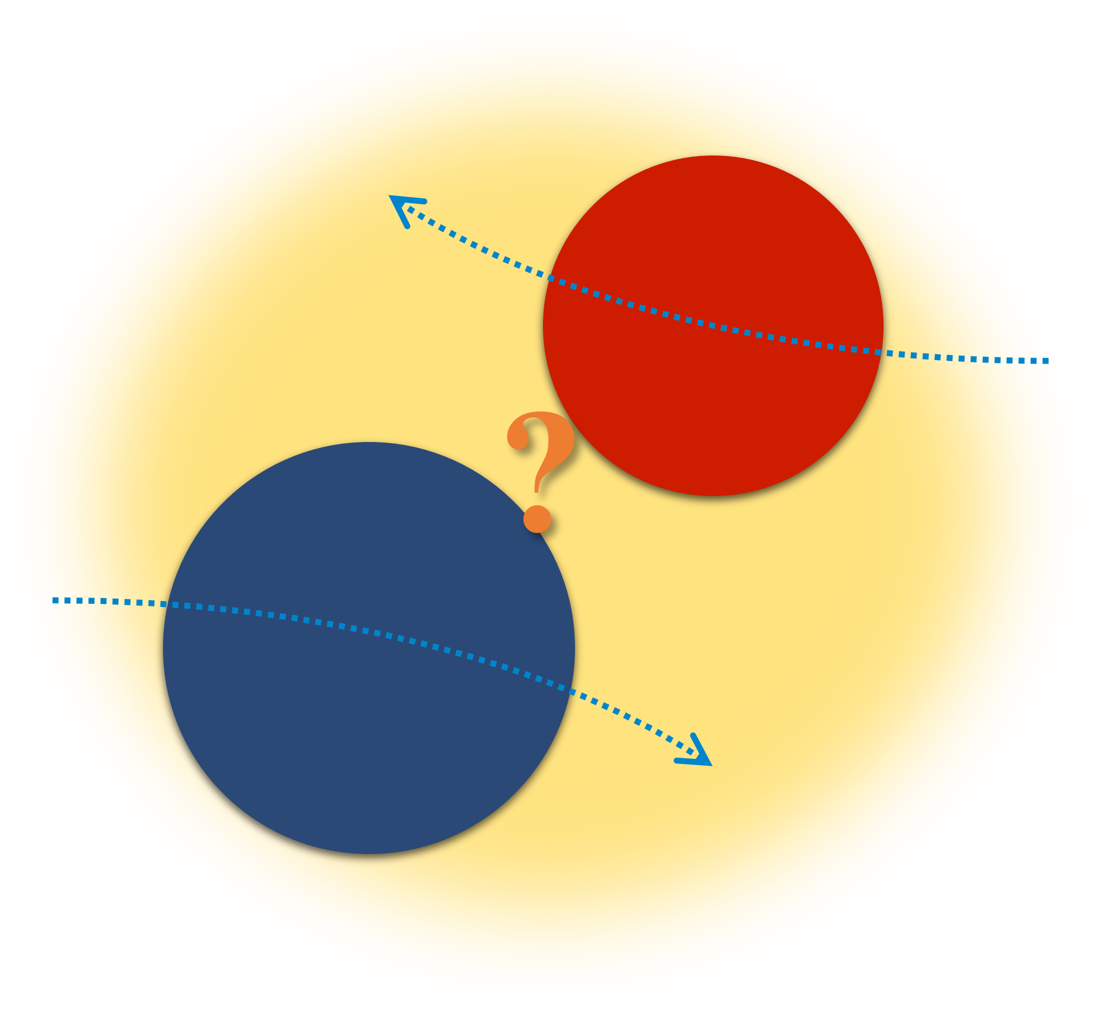
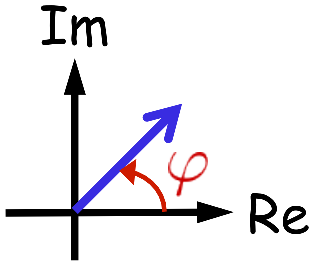
What are the effects of pairing on reaction dynamics?



- More adiabatic dynamics
- Neck formation
- Contact time
- Scattering angle
- Total kinetic energy
- Transfer processes
- …

Dynamical excitations of the pairing field

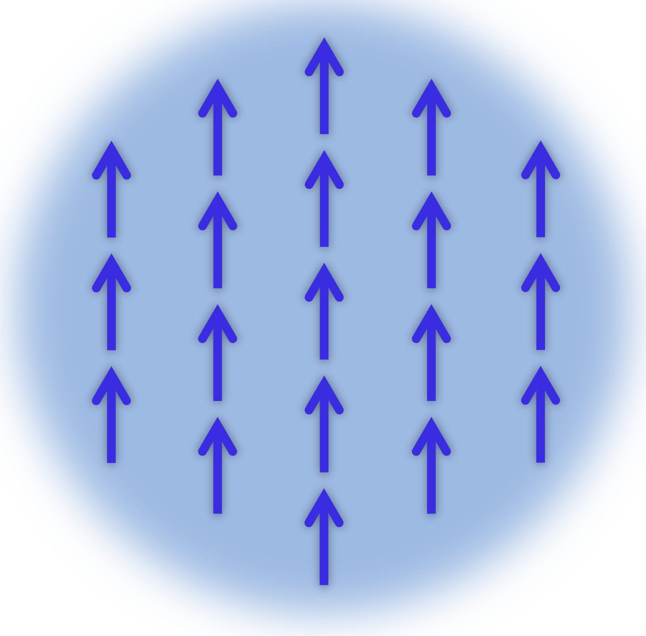
The **Pairing field** may provide variety of **dynamic** excitation modes



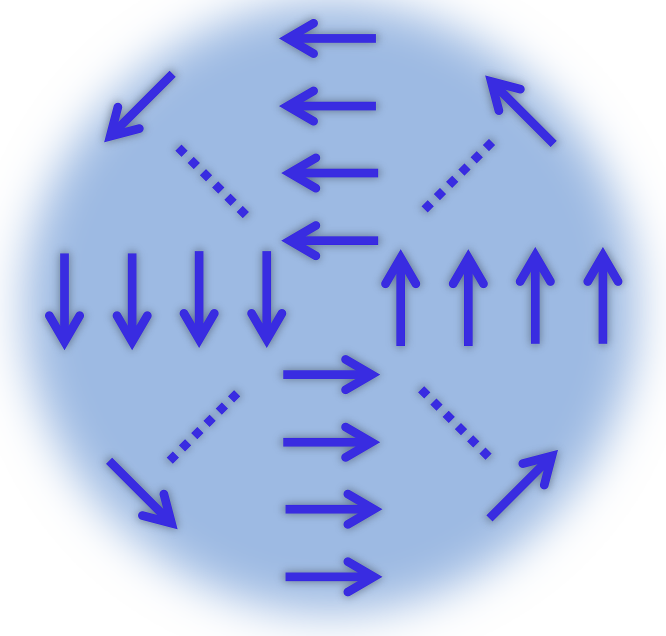
$$|\Delta(\boldsymbol{r},t)|e^{\mathrm{i}\varphi(\boldsymbol{r},t)}$$

**Superfluid velocity*

$$\boldsymbol{v}_s(\boldsymbol{r},t) \propto \boldsymbol{\nabla}\varphi(\boldsymbol{r},t)$$



Collective rotation
(of the phase)



Quantum vortex

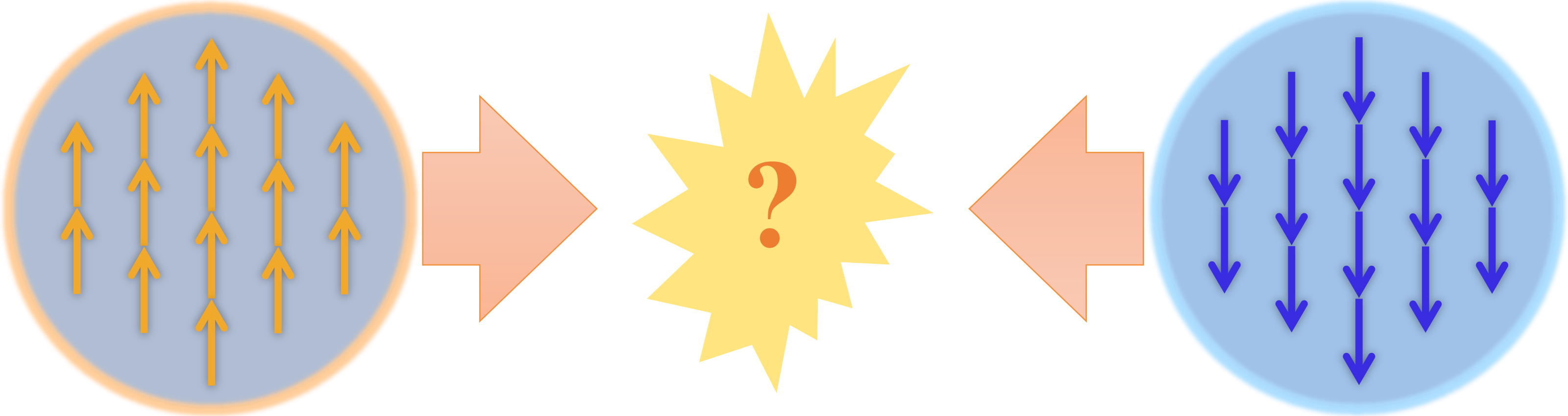
What we have investigated

3D, TDSLDA (TDHFB) calculations for heavy-ion reactions (w/o LS) predicts

Q. What happens when two **superfluid** nuclei with different **phases** collide??

$$\Delta\varphi \ (\equiv \varphi_1 - \varphi_2)$$

$|\Delta_1(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_1(\boldsymbol{r},t)}$ $|\Delta_2(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_2(\boldsymbol{r},t)}$



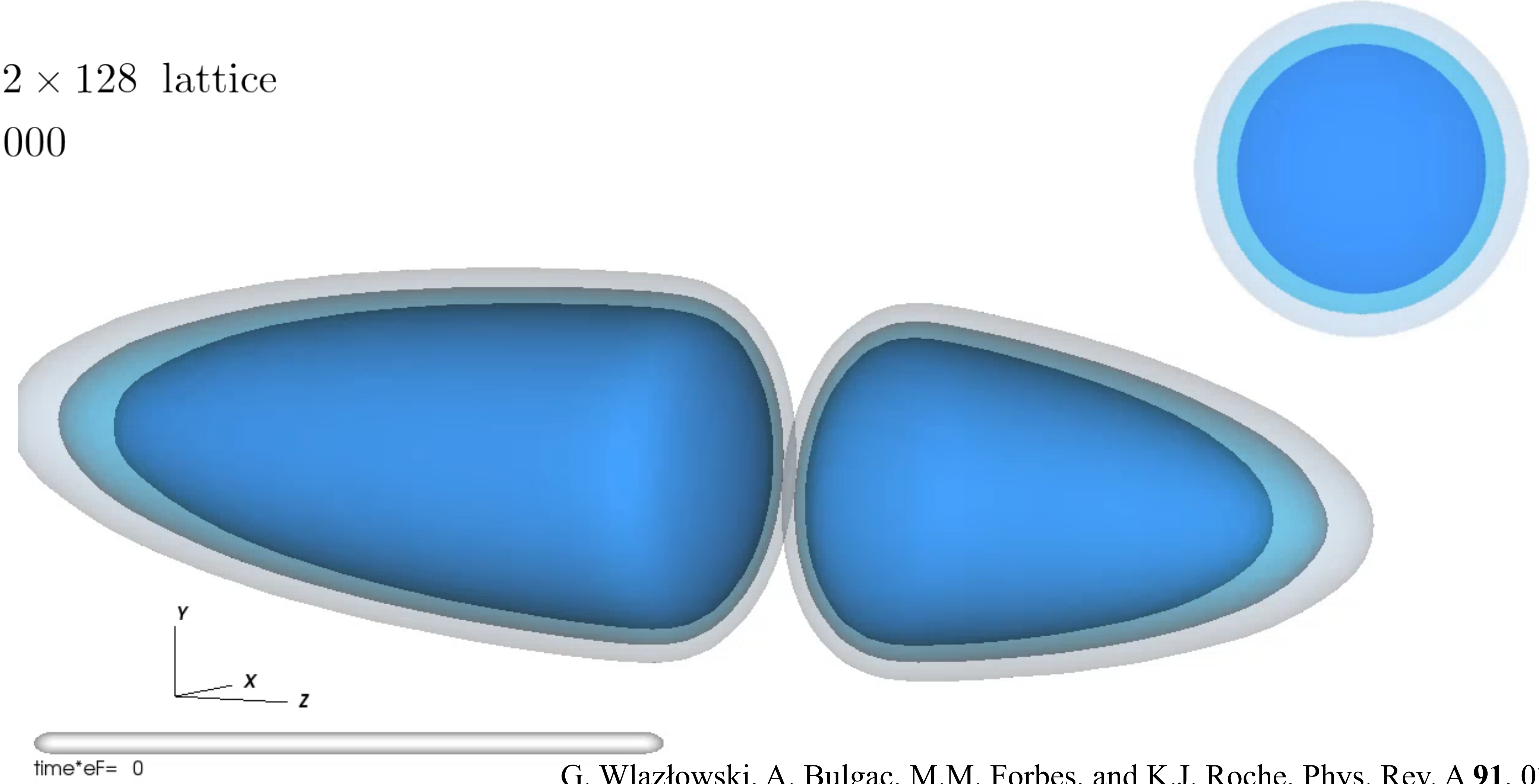
“Solitonic excitations” in cold atomic gases

Result of TDSLDA simulation:

Phase discontinuity creates a vortex ring which decays into a vortex line

$32 \times 32 \times 128$ lattice

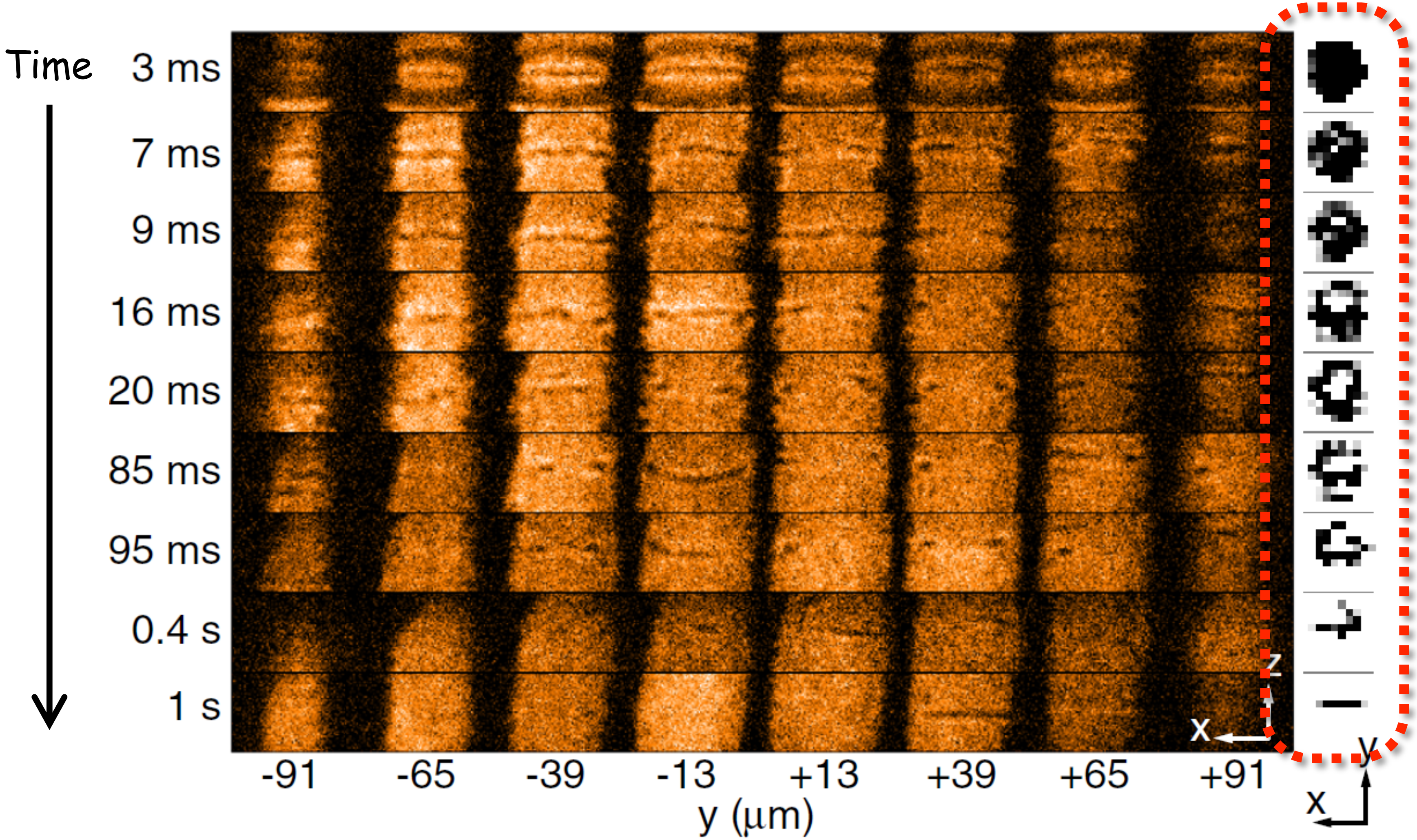
$N \sim 1000$



G. Wlazłowski, A. Bulgac, M.M. Forbes, and K.J. Roche, Phys. Rev. A **91**, 031602 (2015)

"Solitonic excitations" in cold atomic gases

The cascades of solitonic excitations have been identified experimentally



Vortex ring

Vortex line

M.J.H. Ku, B. Mukherjee, T. Yefsah, and M.W. Zwierlein, Phys. Rev. Lett. **116**, 045304 (2016)

Method: TDSLDA (Time-Dependent Superfluid Local Density Approximation

3D, TDSLDA calculations were performed for various phase differences

- TDSLDA equations (formally equivalent to TDHFB or TDBdG equations)

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} u_i(\boldsymbol{r},t) \\ v_i(\boldsymbol{r},t) \end{pmatrix} = \begin{pmatrix} h(\boldsymbol{r},t) & \Delta(\boldsymbol{r},t) \\ \Delta^*(\boldsymbol{r},t) & -h(\boldsymbol{r},t) \end{pmatrix} \begin{pmatrix} u_i(\boldsymbol{r},t) \\ v_i(\boldsymbol{r},t) \end{pmatrix}$$

h : single-particle Hamiltonian

$\Delta(\boldsymbol{r}) = -g_{\text{eff}}(\boldsymbol{r})\nu_c(\boldsymbol{r})$: pairing field

ν : anomalous density

EDF:

Normal part: FaNDF^0 **w/o LS**

Pairing part: $\mathcal{E}_{\text{pair}}(\boldsymbol{r}) = g\left(|\nu_n(\boldsymbol{r})|^2 + |\nu_p(\boldsymbol{r})|^2\right)$

3D box w/o any symmetry restrictions (Δx = 1.25 fm): $64 \times 20 \times 20$ $(80\,\text{fm} \times 25\,\text{fm} \times 25\,\text{fm})$ for $b = 0$

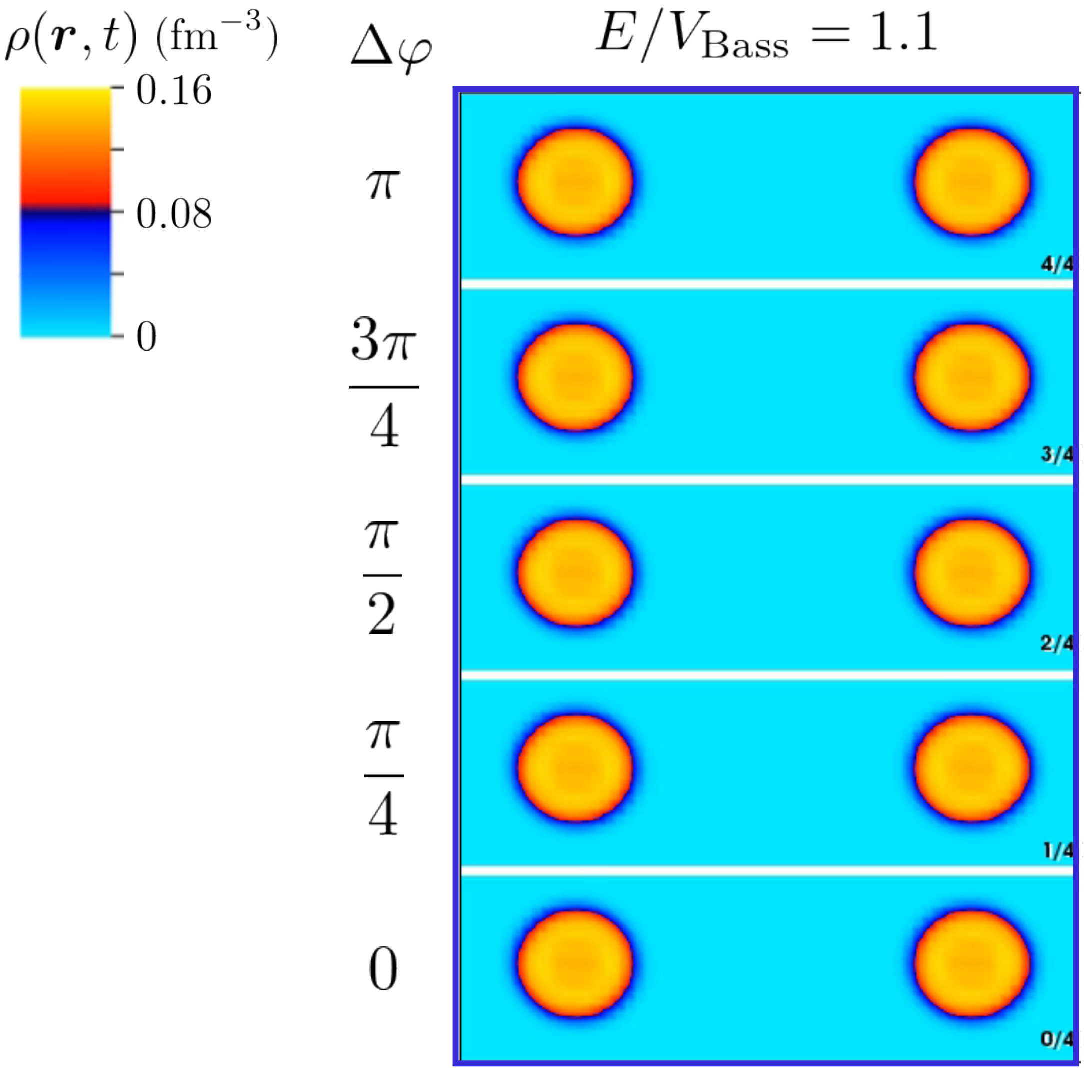
$64 \times 48 \times 20$ $(80\,\text{fm} \times 60\,\text{fm} \times 25\,\text{fm})$ for $b \neq 0$

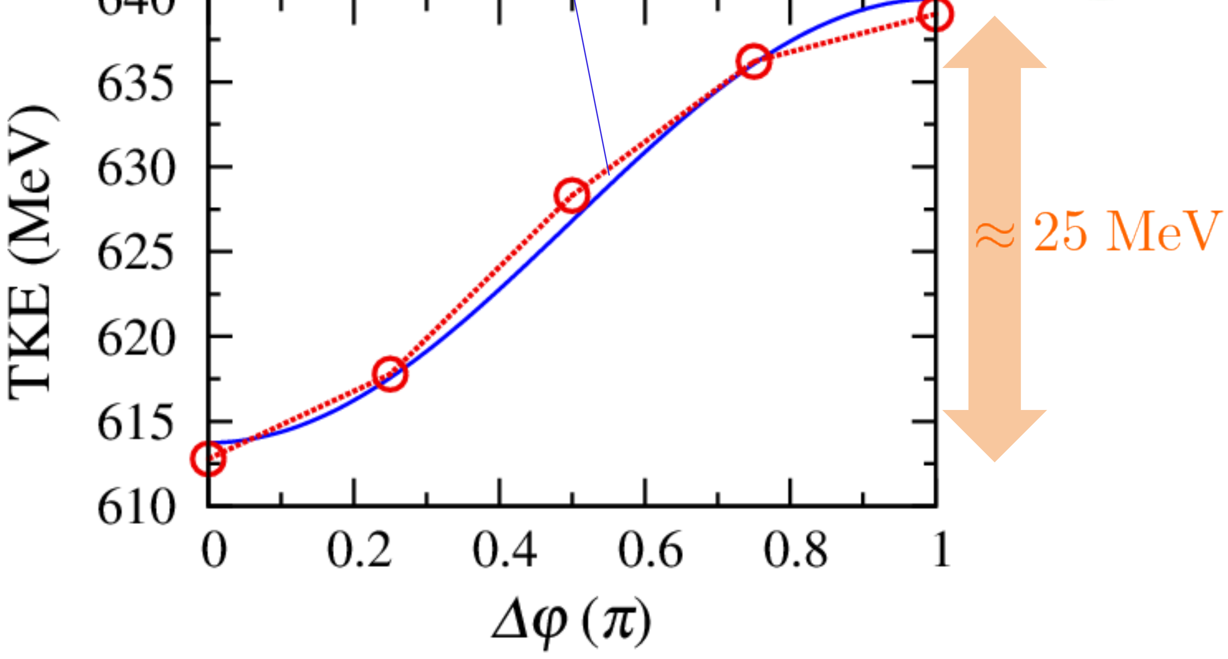
E_c=100 MeV
\# of qpwf ~ 15,000
several hours w/ 32 GPUs for b=0
(on our GPU cluster at WUT)

FaNDF^0: S.A. Fayans et al., JETP Letters **68**(1998)169; NPA**676**(2000)49.
TDSLDA: G. Wlazłowski et al., arXiv:1606.04847 (2016).
Static calc: S. Jin et al., arXiv:1608.03711 (2016).
Renormalization: A. Bulgac and Y. Yu, PRL**88**(2002)042504; PRC**65**(2002)051305(R).

Results: ^{240}Pu+^{240}Pu head-on collisions

Total kinetic energy (TKE) of outgoing fragments changes as large as 25 MeV!!



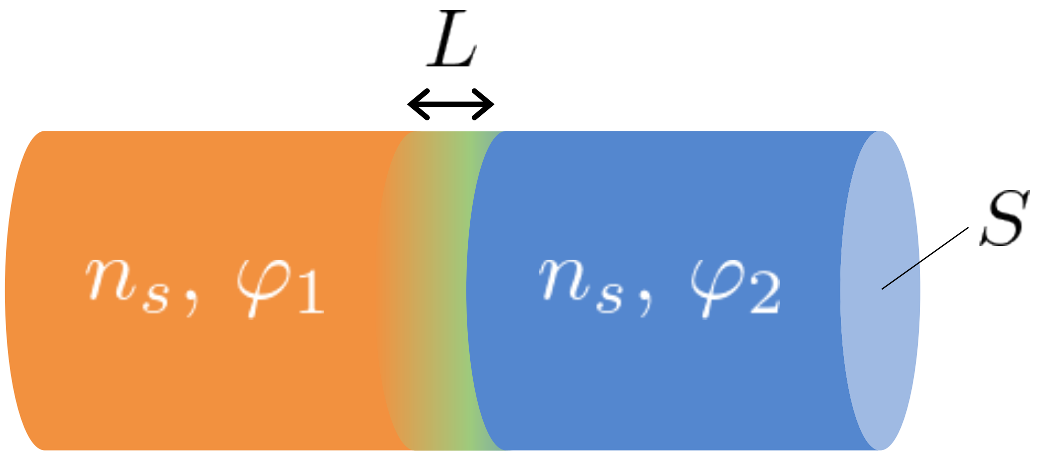


Why??

Additional energy is necessary to attach two superfluids with different phases

- The additional energy cost (derived from Ginzburg-Landau theory)

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



*The energy does not depend on the absolute value of Δ!

S: Attaching area

L: Length scale over which the phase varies

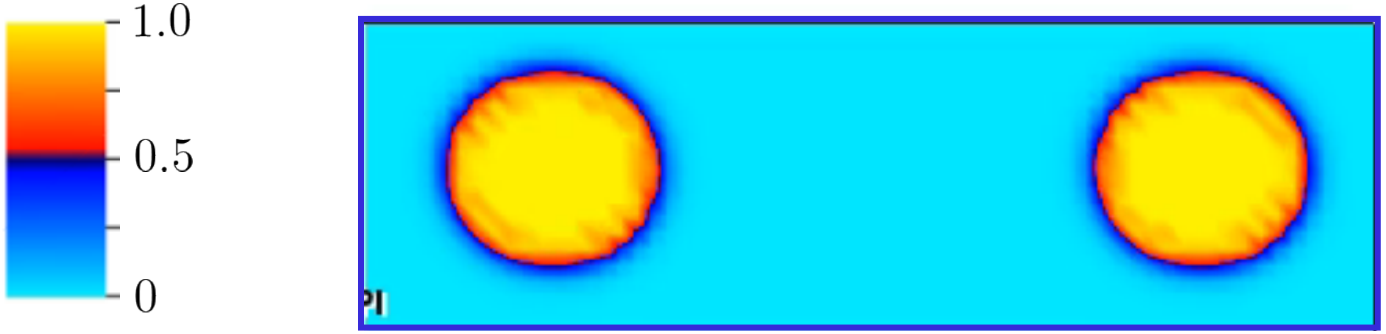
n_s: Superfluid density

e.g.) $S = \pi R^2$, $L \sim R = 6$ fm, $n_s = 0.08$ fm^{-3} $\rightarrow$ $E \sim 30$ MeV

Solitonic excitations

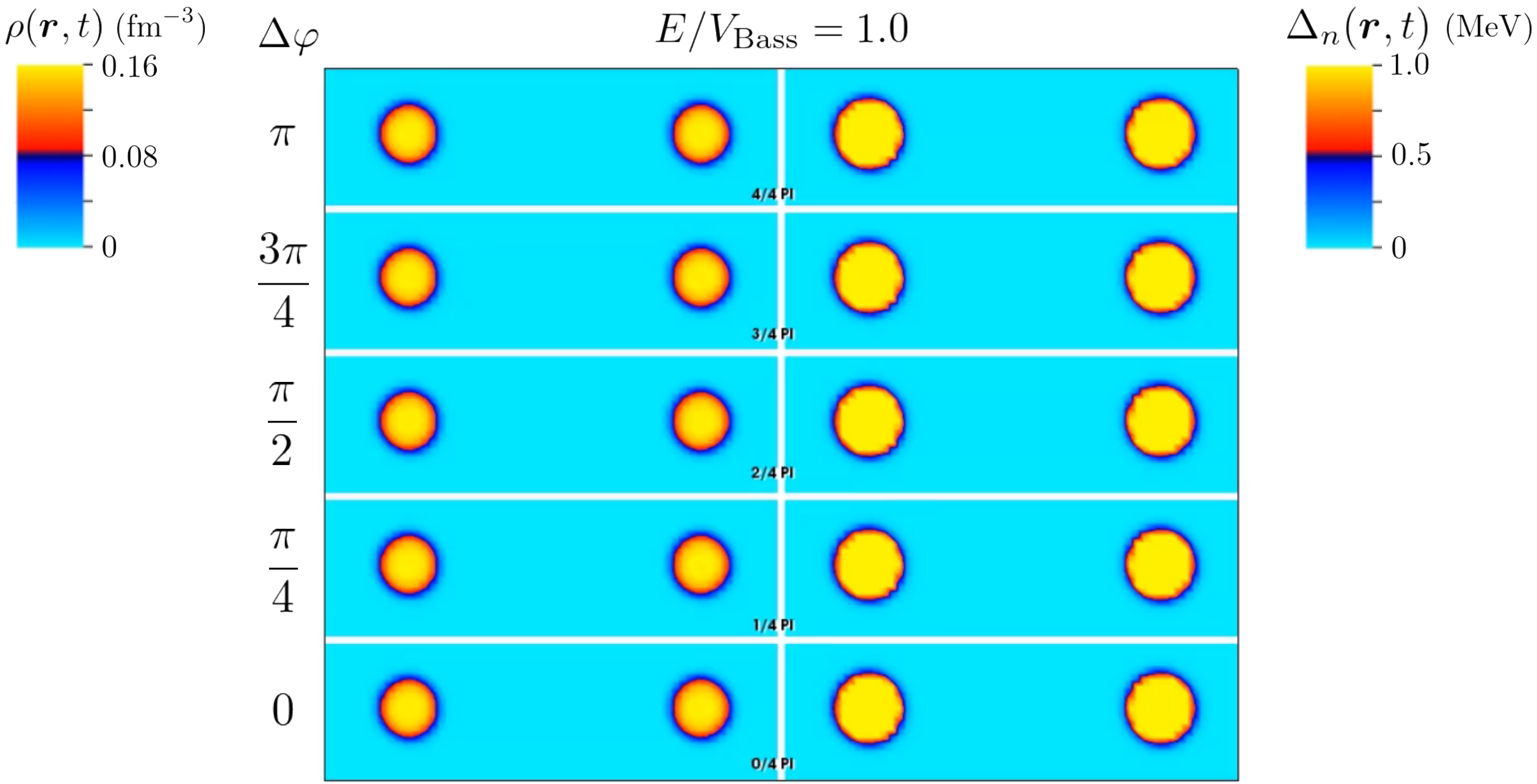
Additional energy is necessary to attach two superfluids with different phases

$\Delta_n(\boldsymbol{r}, t)$ (MeV) $\quad$ ^{240}Pu+^{240}Pu, $\Delta\varphi = \pi$



Results: $^{90}Zr+^{90}Zr$ head-on collisions

The phase difference suppresses the fusion reaction



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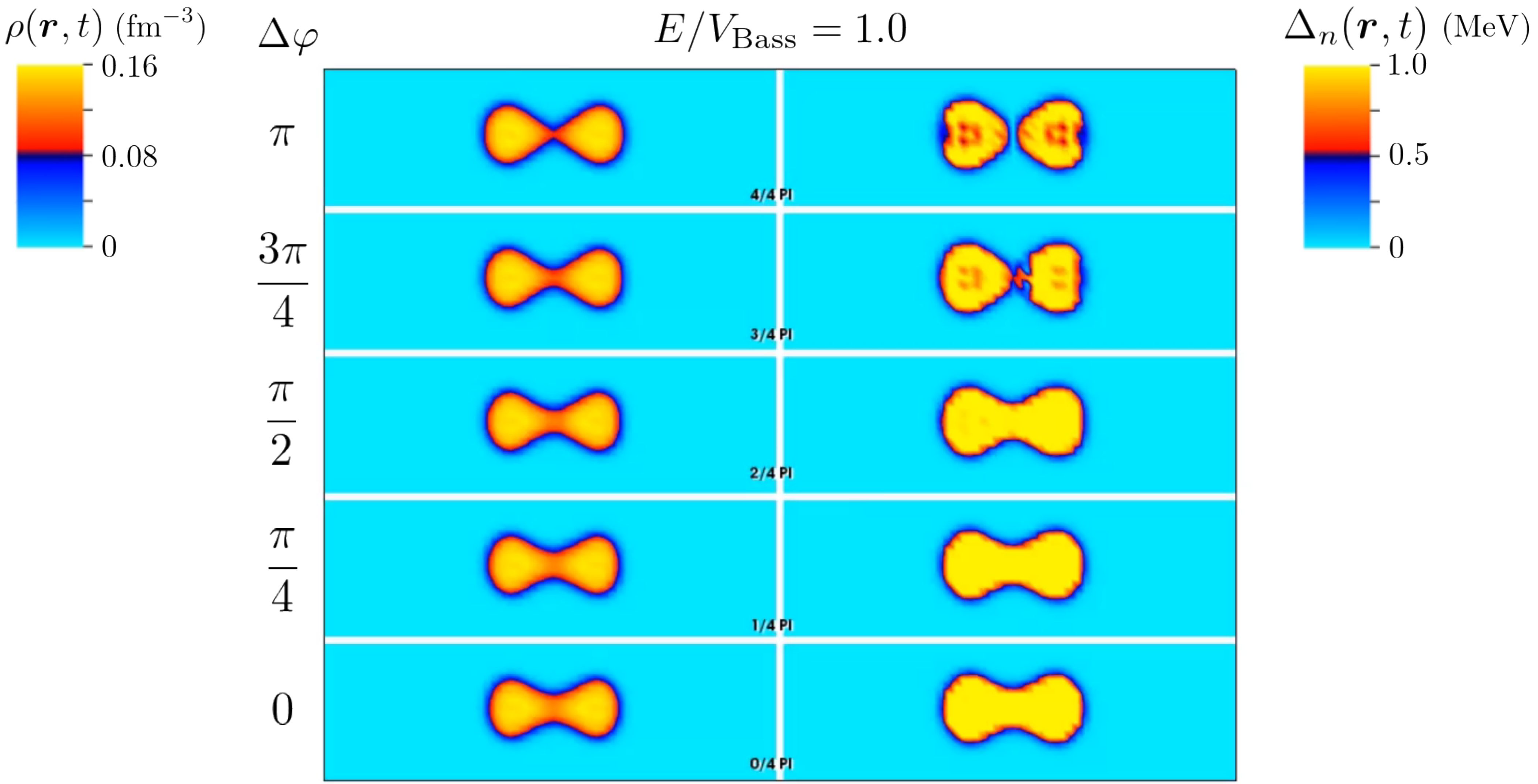
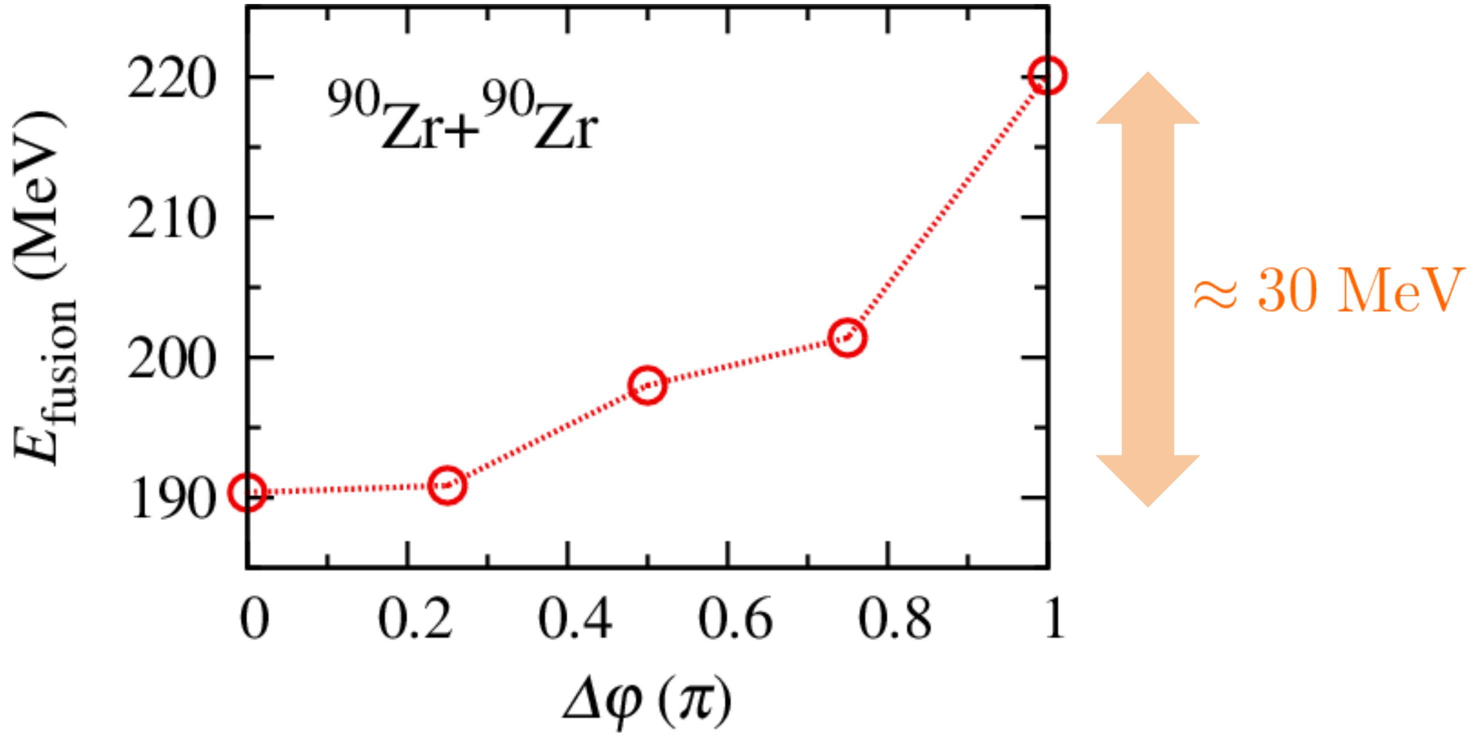


Results: $^{90}Zr+^{90}Zr$ head-on collisions

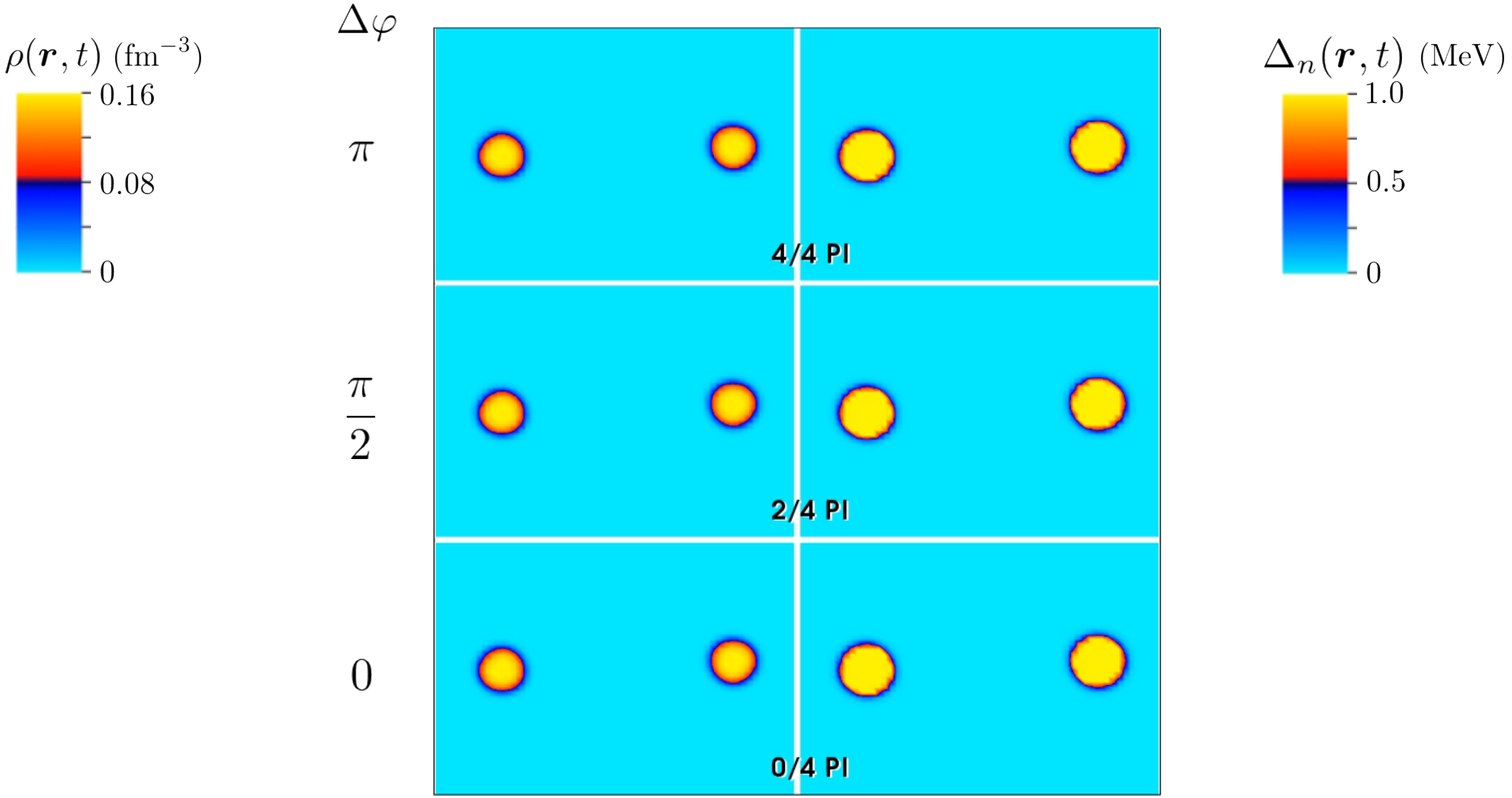
The phase difference suppresses the fusion reaction

*E_{fusion}: the lowest energy at which we observed fusion reaction



Results: $^{90}Zr+^{90}Zr$ non-central collisions

Suppression of the neck formation results in different contact time & scattering angle



Summary

When two superfluid nuclei with different phases collide
solitonic excitations are induced

$$\Delta\varphi \; (\equiv \varphi_1 - \varphi_2)$$

$|\Delta_1(\boldsymbol{r},t)|e^{i\varphi_1(\boldsymbol{r},t)}$ $\quad$ $|\Delta_2(\boldsymbol{r},t)|e^{i\varphi_2(\boldsymbol{r},t)}$

- ✓ Additional energy is necessary (the barrier height is effectively increased)
- ✓ Total kinetic energy is affected by several tens of MeV
- ✓ Fusion reaction is substantially hindered
- ✓ Neck formation is suppressed
- ✓ Scattering angle (contact time) can be changed

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