Modeling superfluidity in neutron stars with Brussels-Montreal functionals

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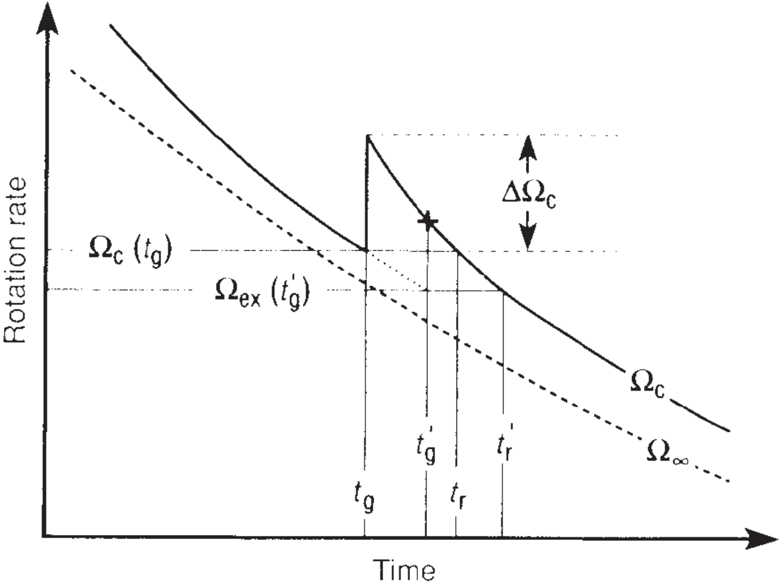
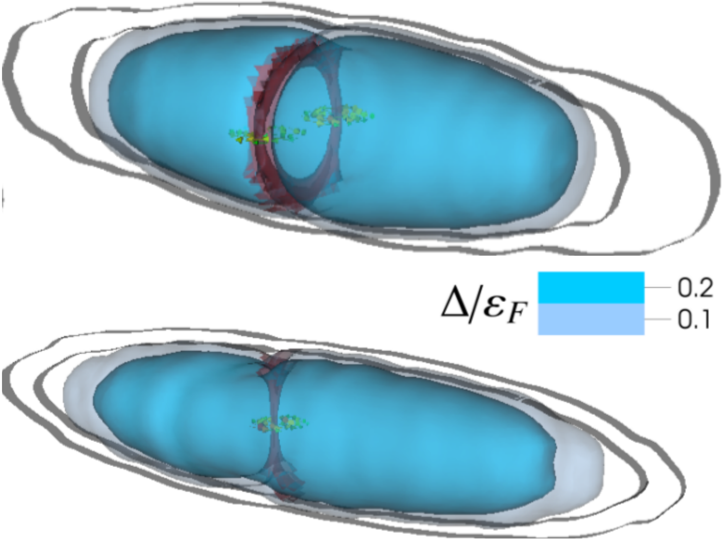
28$^{\text{th}}$ February 2020, Karpacz



Link et al., Nature 359, 616 (1992)



Wlazłowski et al., Phys. Rev. Lett. 120, 253002 (2018)

$$\rho(r) = \sum_k |v_k(r)|^2 \qquad \tau(r) = \sum_k |\nabla v_k(r)|^2 \qquad \nu(r) = \sum_k u_k(r) v_k^*(r)$$

$$h(r) \equiv h(\rho(r), \tau(r), \nabla\rho(r), \vec{j}(r))$$
$$\Delta(r) \equiv \Delta(\rho(r), \nabla\rho(r), \nu(r))$$

Bogolubov-de Gennes equations

$$\begin{pmatrix} h(r) & \Delta(r) \\ \Delta^*(r) & -h^*(r) \end{pmatrix} \begin{pmatrix} u_k(r) \\ v_k(r) \end{pmatrix} = \epsilon_k \begin{pmatrix} u_k(r) \\ v_k(r) \end{pmatrix}$$

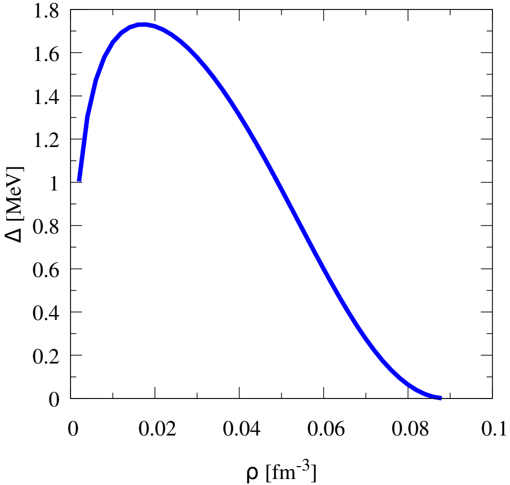
$$\varepsilon(\rho, \vec{\nabla}\rho, \nu, \tau, \boldsymbol{j}) = \frac{\hbar^2}{2M}\tau + \varepsilon_\rho(\rho) + \varepsilon_\tau(\rho, \tau, \boldsymbol{j}) + \varepsilon_{\Delta\rho}(\rho, \vec{\nabla}\rho) + \varepsilon_\pi(\rho, \vec{\nabla}\rho, \nu)$$

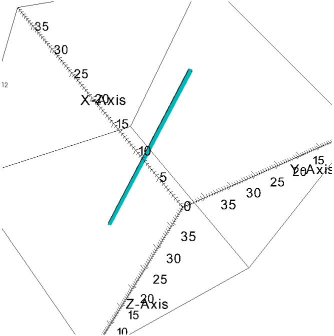
$$\begin{aligned} h(r) &= \frac{\delta\varepsilon}{\delta\rho} - \nabla\frac{\delta\varepsilon}{\delta\tau}\nabla \\ &\quad - \frac{i}{2}\left\{\frac{\delta\varepsilon}{\delta\boldsymbol{j}}, \nabla\right\} \\ \Delta(r) &= \frac{\delta\varepsilon}{\delta\nu} \end{aligned}$$

$$\varepsilon(\rho, \vec{\nabla}\rho, \nu, \tau, \boldsymbol{j}) = \frac{\hbar^2}{2M}\tau + \varepsilon_\rho(\rho) + \varepsilon_\tau(\rho, \tau, \boldsymbol{j}) + \varepsilon_{\Delta\rho}(\rho, \vec{\nabla}\rho) + \varepsilon_\pi(\rho, \vec{\nabla}\rho, \nu)$$

$$h(r) = \frac{\delta\varepsilon}{\delta\rho} - \nabla\frac{\delta\varepsilon}{\delta\tau}\nabla - \frac{i}{2}\left\{\frac{\delta\varepsilon}{\delta\boldsymbol{j}}, \nabla\right\}$$

$$\Delta(r) = \frac{\delta\varepsilon}{\delta\nu}$$

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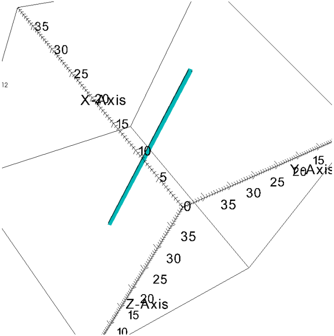
Y-Axis
Z-Axis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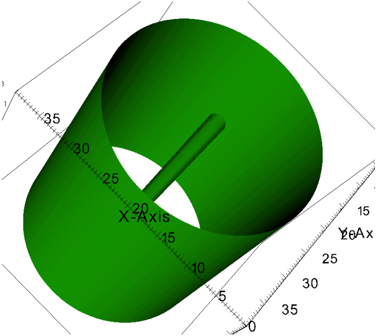
Y-Axis
Z-Axis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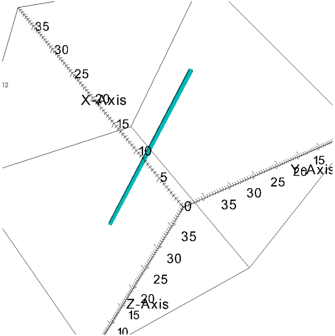
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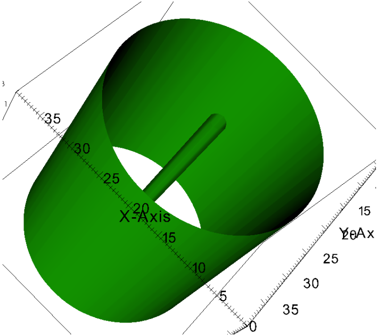
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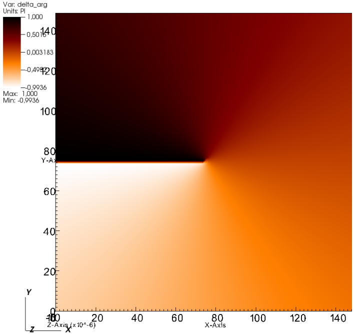
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Units: PI
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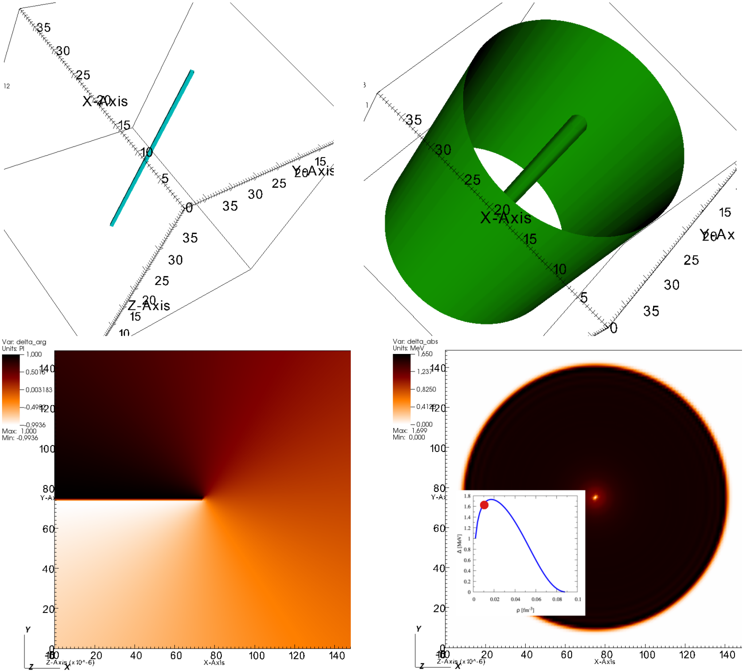
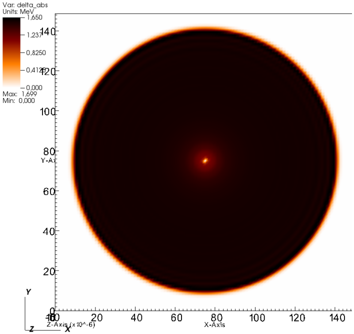
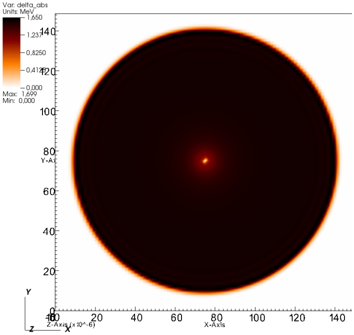
0,5016
0,003183
-0,9936
Max: 1,000
Min: -0,9936
X-Axis

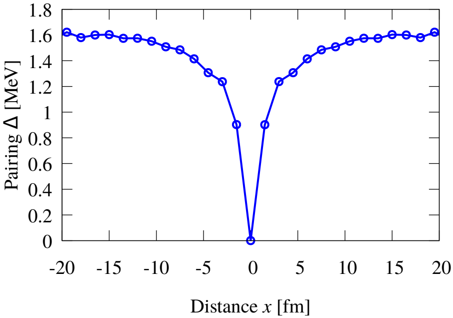


X-Axis
Y-Axis
Z-Axis
Var: delta_arg
Units: PI
1,000
0,5016
0,003183
-0,4952
-0,9936
Max: 1,000
Min: -0,9936
Var: delta_abs
Units: MeV
1,650
1,237
0,8250
0,4125
0,000
Max: 1,699
Min: 0,000
Δ [MeV]
ρ [fm^-3]
(x10^-6)

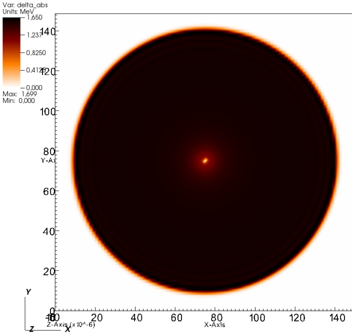

Var: delta_abs
Units: MeV
1.650
1.237
0.8250
0.4125
0.000
Max: 1.699
Min: 0.000
Y-Axis
X-Axis
Z-Axis (x10^-6)
Y
X
Z



Var: delta_abs
Units: MeV
1,650
1,237
0,8250
0,4125
0,000
Max: 1,699
Min: 0,000
Y-Axis
X-Axis
Z-Axis (x10^-6)



Pairing Δ [MeV]
Distance x [fm]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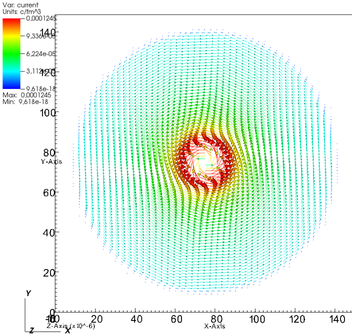
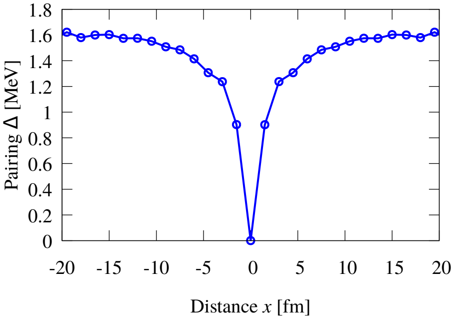
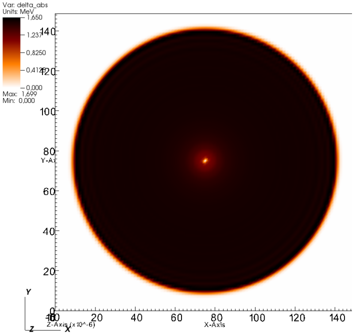
1,237
0,8250
0,4125
0,000
Max: 1,699
Min: 0,000
Y-Axis
X-Axis
Z-Axis (x10^-6)


Var: current
Units: c/fm^3
0,0001245
9,336e-05
6,224e-05
3,112e-05
9,618e-18
Max: 0,0001245
Min: 9,618e-18
Y-Axis
X-Axis
Z-Axis (x10^-6)


Pairing Δ [MeV]
Distance x [fm]


Var: delta_abs
Units: MeV
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1,237
0,8250
0,4125
0,000
Max: 1,699
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Y-Axis
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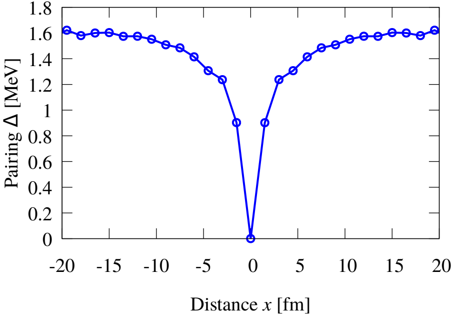
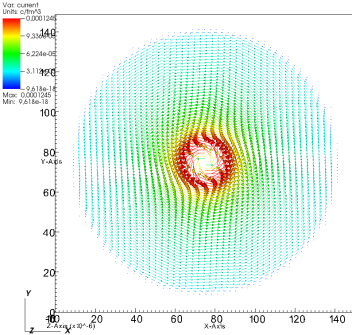
Z-Axis (x10^-6)


Pairing Δ [MeV]
Distance x [fm]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0,0001245
9,336e-05
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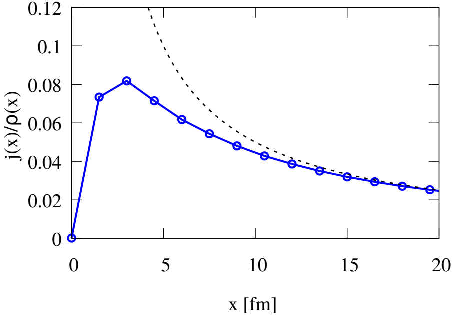
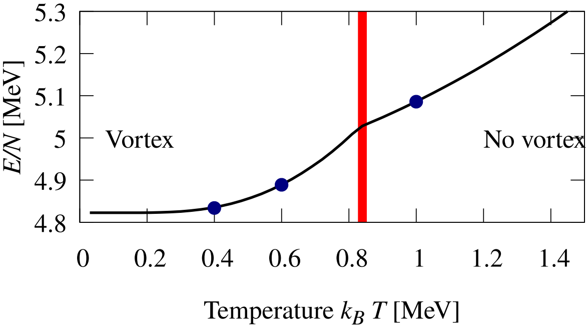
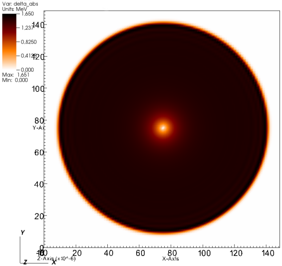
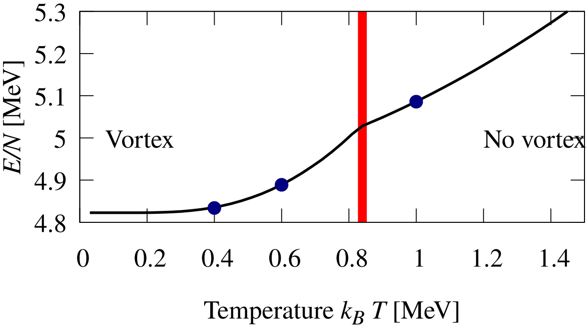
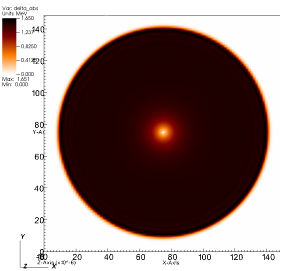
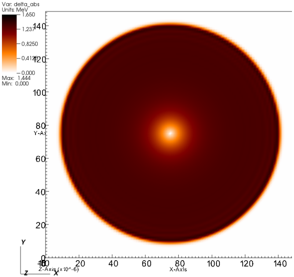

j(x)/ρ(x)
x [fm]

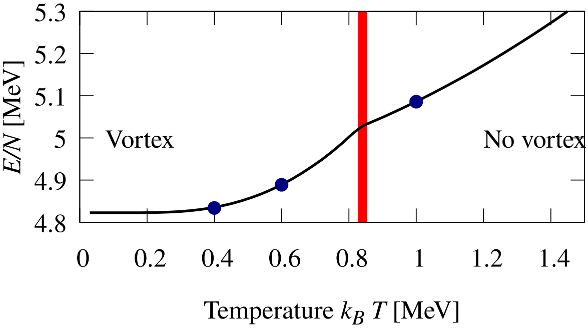

E/N [MeV]
5.3
5.2
5.1
5
4.9
4.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Vortex
No vortex
Temperature k_B T [MeV]


Var: delta_abs
Units: MeV
Max: 1.651
Min: 0.000
X-Axis

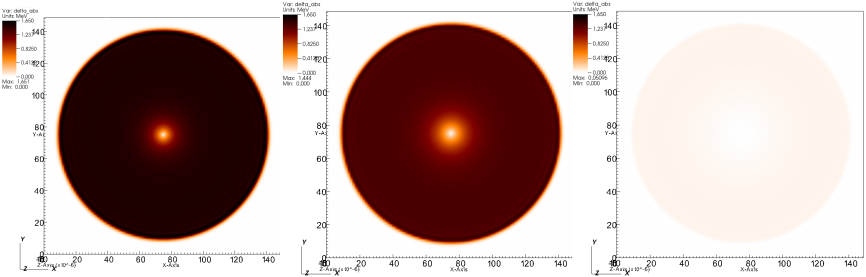

E/N [MeV]
5.3
5.2
5.1
5
4.9
4.8
Vortex
No vortex
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Temperature k_B T [MeV]


Var: delta_abs
Units: MeV
Max: 1,651
Min: 0,000
X-Axis


Var: delta_abs
Units: MeV
Max: 1,444
Min: 0,000
X-Axis

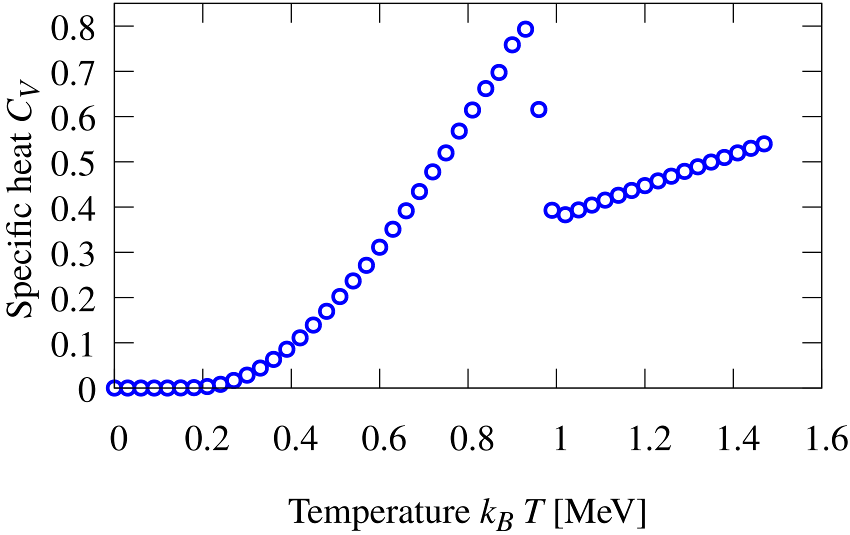


5.3
5.2
5.1
5
4.9
4.8
E/N [MeV]
Vortex
No vortex
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Temperature k_B T [MeV]



Var: delta_abs
Units: MeV
Max: 1.651
Min: 0.000
Var: delta_abs
Units: MeV
Max: 1.444
Min: 0.000
Var: delta_abs
Units: MeV
Max: 0.05096
Min: 0.000
X-Axis

$$C_V = \frac{\partial E}{\partial T}$$



Outlook

★ heat capacity

★ full 3D dynamics

★ energy dissipation

★ polarized system

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- ★ full 3D dynamics
- ★ energy dissipation
- ★ polarized system

Take-home message

- ★ BSk fitted for both regimes: neutron matter and nuclei (clusters & vortices)
- ★ beyond mean-field
- ★ finite temperatures
- ★ dynamics

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★ full 3D dynamics

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Thank you!