Dynamics in the inner crust: heavy impurity in Fermi superfluid

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April 30^{th} 2025, CAMK, Warszawa

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Piotr Magierski


Gabriel Wlazłowski


Agata Zdanowicz

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Nicolas Chamel

Physical Review X 14, 041054 (2024)

LUMI PL GRID NARODOWE CENTRUM NAUKI

PLGrid LUMI PLL/2022/03/016433 ★ NCN 2021/40/C/ST2/00072

Functionalities Download Gallery Publications and Materials Related projects Info EN

Warsaw University of Technology | **W-SLDA Toolkit W-BSk Toolkit**

W-SLDA Toolkit

Self-consistent solver of mathematical problems which have structure formally equivalent to Bogoliubov-de Gennes equations.

static problems: st-wslda

$$\begin{pmatrix} h_a(\boldsymbol{r}) - \mu_a & \Delta(\boldsymbol{r}) \\ \Delta^*(\boldsymbol{r}) & -h_b^*(\boldsymbol{r}) + \mu_b \end{pmatrix} \begin{pmatrix} u_n(\boldsymbol{r}) \\ v_n(\boldsymbol{r}) \end{pmatrix} = E_n \begin{pmatrix} u_n(\boldsymbol{r}) \\ v_n(\boldsymbol{r}) \end{pmatrix}$$

time-dependent problems: td-wslda

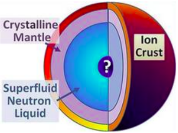
$$i\hbar \frac{\partial}{\partial t} \begin{pmatrix} u_n(\boldsymbol{r},t) \\ v_n(\boldsymbol{r},t) \end{pmatrix} = \begin{pmatrix} h_a(\boldsymbol{r},t) - \mu_a & \Delta(\boldsymbol{r},t) \\ \Delta^*(\boldsymbol{r},t) & -h_b^*(\boldsymbol{r},t) + \mu_b \end{pmatrix} \begin{pmatrix} u_n(\boldsymbol{r},t) \\ v_n(\boldsymbol{r},t) \end{pmatrix}$$

Extension to nuclear matter in neutron stars

Unified solvers for static and time-dependent problems

Dimensionalities of problems: 3D, 2D and 1D

Extension to nuclear matter in neutron stars



The W-SLDA Toolkit has been expanded to encompa
available as the W-BSk Toolkit.

ALL FUNCTIONALITIES →

Integration with VisIt: visualization, animation and analysis tool

ce

Getting the code

DOWNLOAD

The W-SLDA & W-BSk Toolkits are free to download. It is published as open source under GNU GPL License. In order to get W-SLDA or W-BSk Toolkit click "Read more" and follow instructions.

READ MORE →

W-BSk Toolkit

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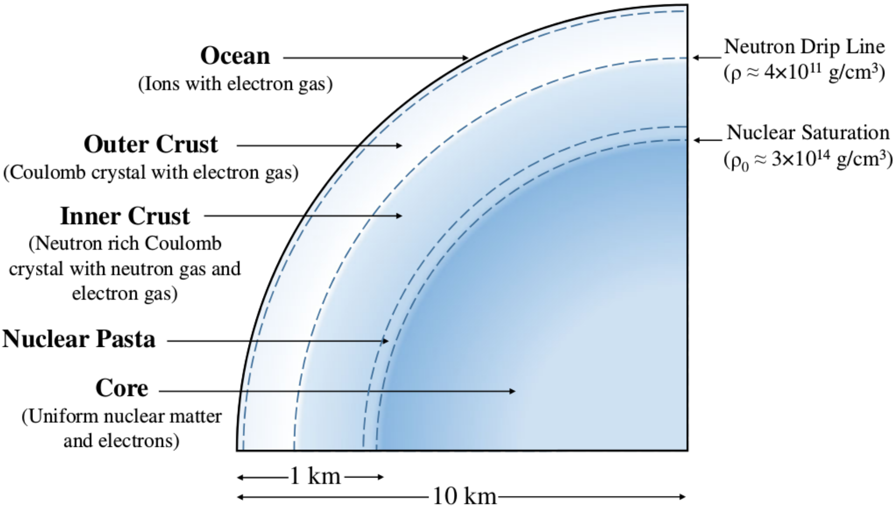
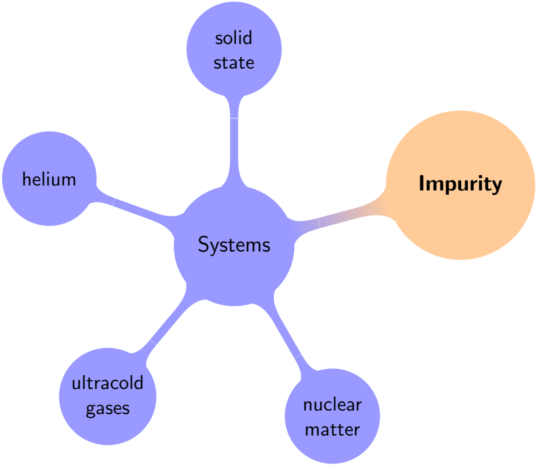
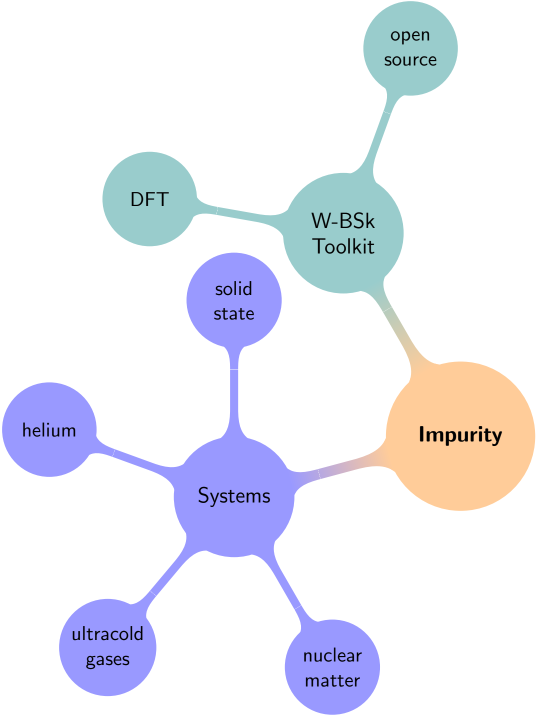
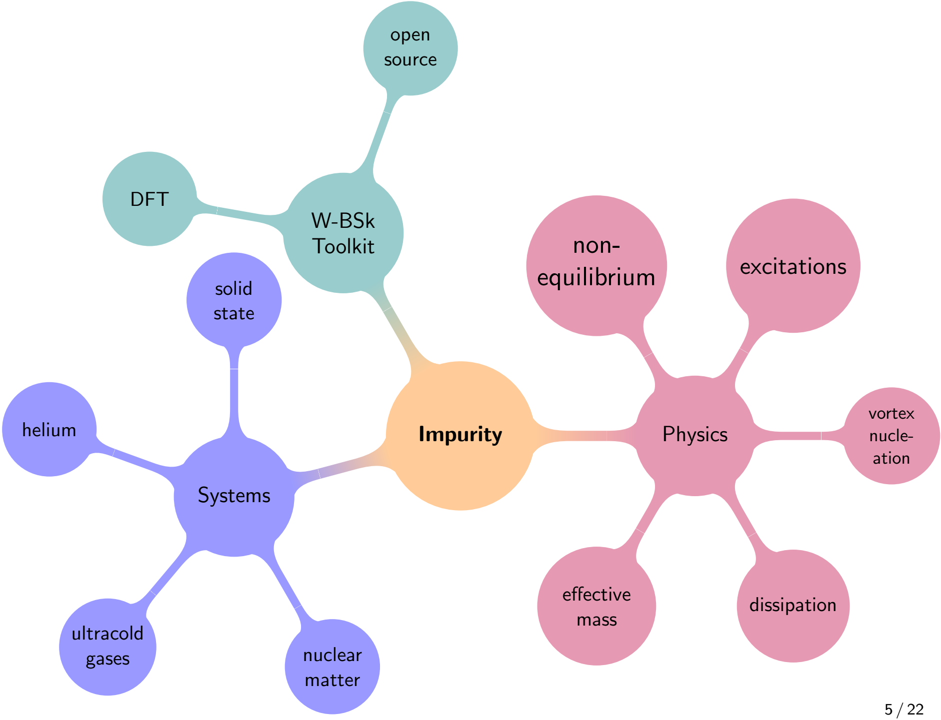
Changelog



Caplan, M. E., and C. J. Horowitz, Reviews of Modern Physics 89, 041002 (2017)


solid
state
helium
Impurity
Systems
ultracold
gases
nuclear
matter


open source
W-BSk Toolkit
DFT
solid state
helium
Impurity
Systems
ultracold gases
nuclear matter


open
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nuclear
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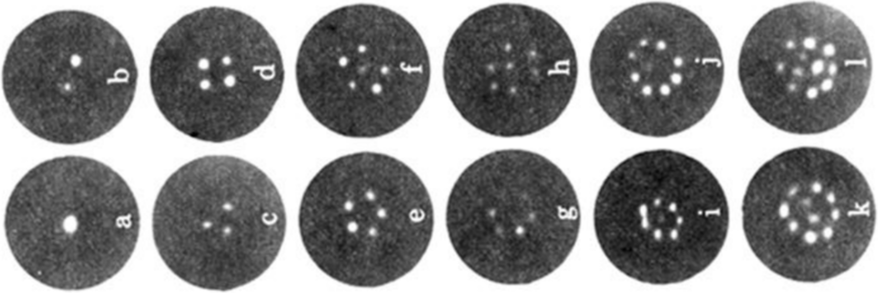
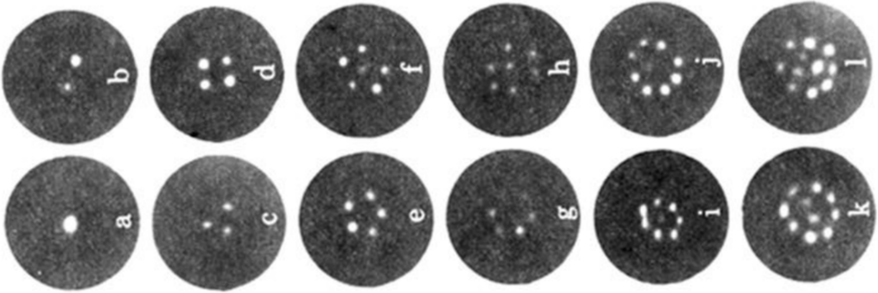


E. J. Yarmchuk, M. J. V. Gordon, and R. E. Packard, Physical Review Letters 43, 214 (1979)



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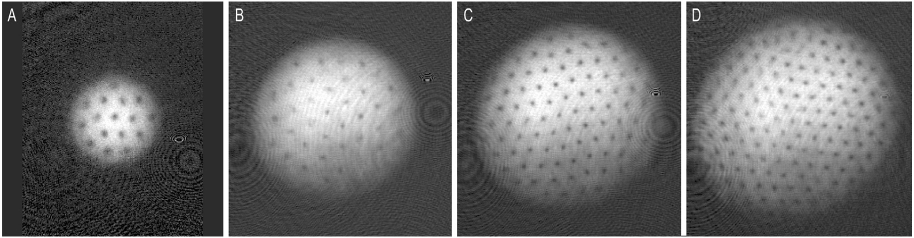
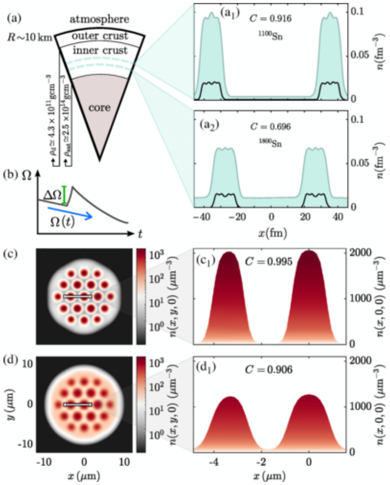
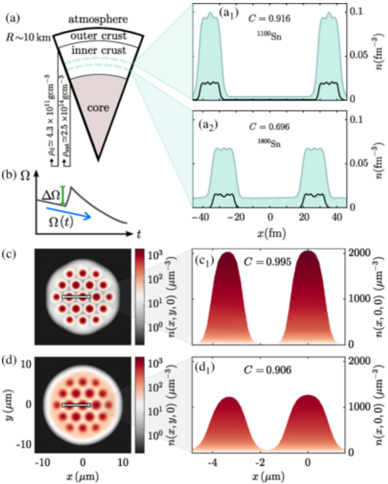
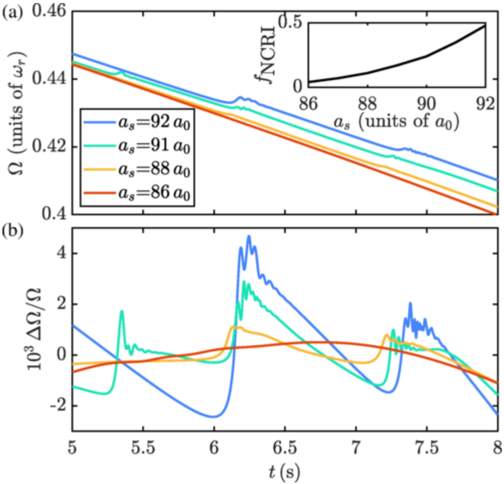


J. R. Abo-Shaeer, C. Raman, J. M. Vogels, W. Ketterle, Science 292, 476 (2001)



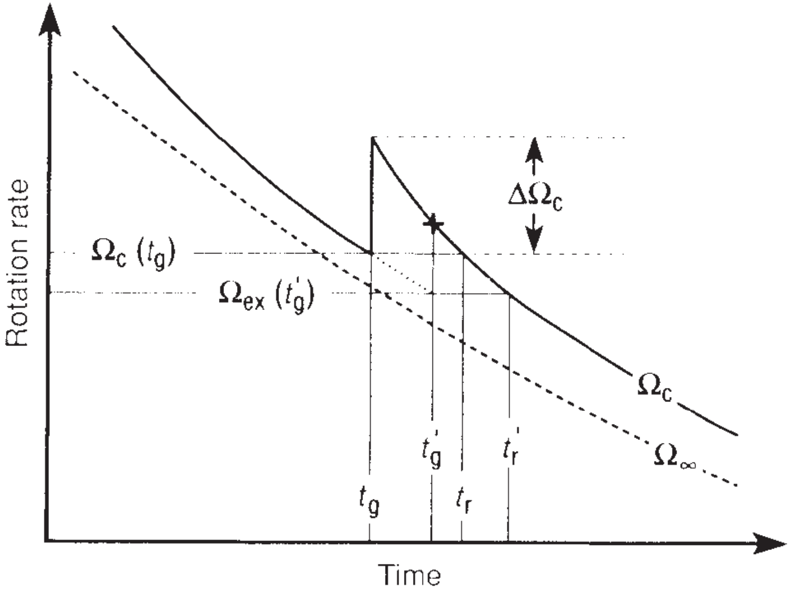
(a)
atmosphere
$R\sim 10$ km
outer crust
inner crust
core
$\rho_d \simeq 4.3\times10^{11}\,\mathrm{gcm^{-3}}$
$\rho_{sat} \simeq 2.5\times10^{14}\,\mathrm{gcm^{-3}}$
(b) Ω
$\Delta\Omega$
$\Omega(t)$
t
(a$_1$) $C = 0.916$
^{1100}Sn
(a$_2$) $C = 0.696$
^{1800}Sn
$n(\mathrm{fm}^{-3})$
x(fm)
(c)
(c$_1$) $C = 0.995$
$n(x, y, 0)$ (μm^{-3})
$n(x, 0, 0)$ (μm^{-3})
(d)
(d$_1$) $C = 0.906$
y (μm)
x (μm)



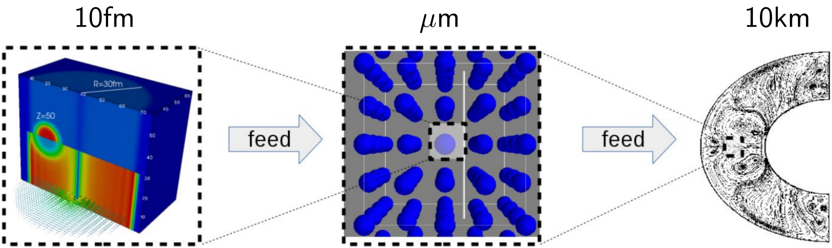


Poli, Elena, et al. "Glitches in rotating supersolids." Physical Review Letters 131, 223401 (2023)

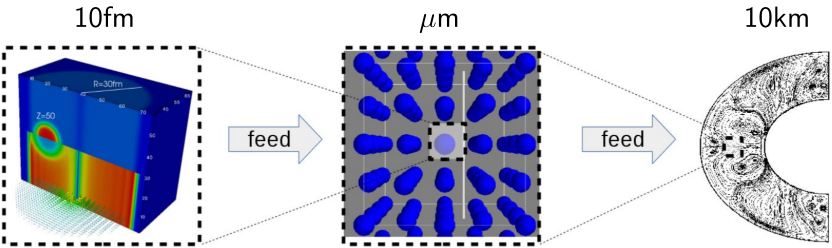
Glitch



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



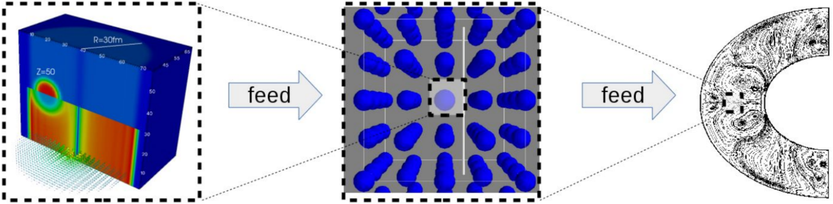
10fm
μm
10km
R=30fm
Z=50
feed
feed



LUMI, Finland (#5 Top 500)

Piz Daint, Switzerland (#37 Top 500)

10fm μm 10km



LUMI, Finland (#5 Top 500)

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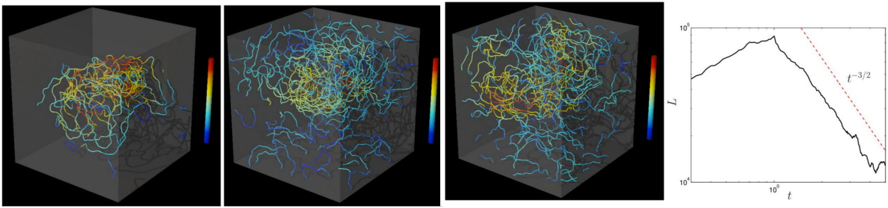


R. Hänninen, A. W. Baggaley, Proc. Nat. Acad. Sci. U.S.A. 111, 4667 (2014)

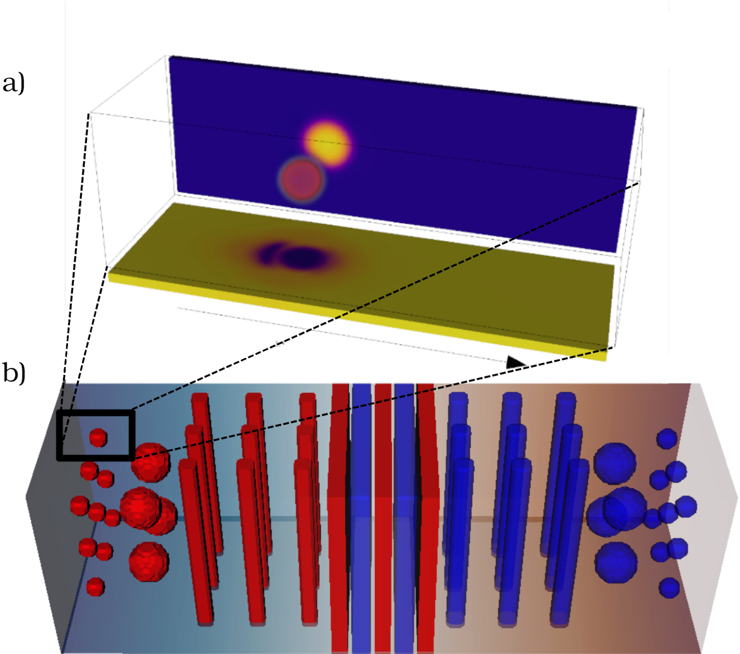
Crust composition

$\rho_{\max}$ [g cm^{-3}]	Element	Z	N	R_{cell} [fm]
8.02×10^{6}	^{56}Fe	26	30	1404.05
2.71×10^{8}	^{62}Ni	28	34	449.48
1.33×10^{9}	^{64}Ni	28	36	266.97
1.50×10^{9}	^{66}Ni	28	38	259.26
3.09×10^{9}	^{86}Kr	36	50	222.66
1.06×10^{10}	^{84}Se	34	50	146.56
2.79×10^{10}	^{82}Ge	32	50	105.23
6.07×10^{10}	^{80}Zn	30	50	80.58
8.46×10^{10}	^{82}Zn	30	52	72.77
9.67×10^{10}	^{128}Pd	46	82	80.77
1.47×10^{11}	^{126}Ru	44	82	69.81
2.11×10^{11}	^{124}Mo	42	82	61.71
2.89×10^{11}	^{122}Zr	40	82	55.22
3.97×10^{11}	^{120}Sr	38	82	49.37
4.27×10^{11}	^{118}Kr	36	82	47.92

ρ [g cm^{-3}]	Element	Z	N	R_{cell} [fm]
4.67×10^{11}	^{180}Zr	40	140	53.60
6.69×10^{11}	^{200}Zr	40	160	49.24
1.00×10^{12}	^{250}Zr	40	210	46.33
1.47×10^{12}	^{320}Zr	40	280	44.30
2.66×10^{12}	^{500}Zr	40	460	42.16
6.24×10^{12}	^{950}Sn	50	900	39.32
9.65×10^{12}	^{1100}Sn	50	1050	35.70
1.49×10^{13}	^{1350}Sn	50	1300	33.07
3.41×10^{13}	^{1800}Sn	50	1750	27.61
7.94×10^{13}	^{1500}Zr	40	1460	19.61
1.32×10^{14}	^{982}Ge	32	950	14.38

Nicolas Chamel and Pawel Haensel. "Physics of neutron star crusts." Living Reviews in relativity 11.1 (2008): 1-182.

Nonequilibrium dynamics



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

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

$$\rho(r) = \sum_k |v_k(r)|^2$$

$$\tau(r) = \sum_k |\nabla v_k(r)|^2$$

$$\nu(r) = \sum_k u_k(r) v_k^*(r)$$

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

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$$\nu(r) = \sum_k u_k(r) v_k^*(r)$$

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

Superfluid **L**ocal **D**ensity **A**pproximation

A. Bulgac, Physical Review A **76**, 040502 (2007)

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Superfluid **L**ocal **D**ensity **A**pproximation

A. Bulgac, Physical Review A **76**, 040502 (2007)

Hartree-Fock-Bogoliubov equations

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

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

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Hartree-Fock-Bogoliubov equations

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Quality of results highly depends on the quality of density functional!

1. Energy density

Under the assumption of invariance under time reversal, the HFB energy is written as the integral of a purely local energy-density functional

$$E_{\rm HFB} = \int \mathcal{E}_{\rm HFB}(\boldsymbol{r})\,{\rm d}^3\boldsymbol{r}, \tag{A1}$$

where

$$\begin{aligned}\mathcal{E}_{\rm HFB}(\boldsymbol{r}) = {} & \mathcal{E}_{\rm Sky}[\rho_n(\boldsymbol{r}), \boldsymbol{\nabla}\rho_n(\boldsymbol{r}), \tau_n(\boldsymbol{r}), \mathbf{J}_n(\boldsymbol{r}), \rho_p(\boldsymbol{r}), \boldsymbol{\nabla}\rho_p(\boldsymbol{r}),\\ & \tau_p(\boldsymbol{r}), \mathbf{J}_p(\boldsymbol{r})] + \mathcal{E}_{\rm Coul}[\rho_p(\boldsymbol{r})]\\ & + \mathcal{E}_{\rm pair}[\rho_n(\boldsymbol{r}), \tilde{\rho}_n(\boldsymbol{r}), \rho_p(\boldsymbol{r}), \tilde{\rho}_p(\boldsymbol{r})].\end{aligned} \tag{A2}$$

The first term here, the energy density for the Skyrme force of this paper, is given by

$$\begin{aligned}\mathcal{E}_{\rm Sky} = {} & \sum_{q=n,p}\frac{\hbar^2}{2M_q}\tau_q + \frac{1}{2}t_0\left[\left(1+\frac{1}{2}x_0\right)\rho^2 - \left(\frac{1}{2}+x_0\right)\sum_{q=n,p}\rho_q^2\right] + \frac{1}{4}t_1\left\{\left(1+\frac{1}{2}x_1\right)\left[\rho\tau + \frac{3}{4}(\nabla\rho)^2\right]\right.\\
& \left. - \left(\frac{1}{2}+x_1\right)\sum_{q=n,p}\left[\rho_q\tau_q + \frac{3}{4}(\nabla\rho_q)^2\right]\right\} + \frac{1}{4}t_2\left\{\left(1+\frac{1}{2}x_2\right)\left[\rho\tau - \frac{1}{4}(\nabla\rho)^2\right] + \left(\frac{1}{2}+x_2\right)\right.\\
& \left. \times \sum_{q=n,p}\left[\rho_q\tau_q - \frac{1}{4}(\nabla\rho_q)^2\right]\right\} + \frac{1}{12}t_3\rho^\alpha\left[\left(1+\frac{1}{2}x_3\right)\rho^2 - \left(\frac{1}{2}+x_3\right)\sum_{q=n,p}\rho_q^2\right]\\
& + \frac{1}{4}t_4\left\{\left(1+\frac{1}{2}x_4\right)\left[\rho\tau + \frac{3}{4}(\nabla\rho)^2\right] - \left(\frac{1}{2}+x_4\right)\sum_{q=n,p}\left[\rho_q\tau_q + \frac{3}{4}(\nabla\rho_q)^2\right]\right\}\rho^\beta\\
& + \frac{\beta}{8}t_4\left[\left(1+\frac{1}{2}x_4\right)\rho(\nabla\rho)^2 - \left(\frac{1}{2}+x_4\right)\boldsymbol{\nabla}\rho\cdot\sum_{q=n,p}\rho_q\boldsymbol{\nabla}\rho_q\right]\rho^{\beta-1} + \frac{1}{4}t_5\left\{\left(1+\frac{1}{2}x_5\right)\left[\rho\tau - \frac{1}{4}(\nabla\rho)^2\right]\right.\\
& \left. + \left(\frac{1}{2}+x_5\right)\sum_{q=n,p}\left[\rho_q\tau_q - \frac{1}{4}(\nabla\rho_q)^2\right]\right\}\rho^\gamma - \frac{1}{16}(t_1x_1+t_2x_2)\,J^2 + \frac{1}{16}(t_1-t_2)\sum_{q=n,p}J_q^2\\
& - \frac{1}{16}(t_4x_4\rho^\beta + t_5x_5\rho^\gamma)J^2 + \frac{1}{16}(t_4\rho^\beta - t_5\rho^\gamma)\sum_{q=n,p}J_q^2 + \frac{1}{2}W_0\left(\boldsymbol{J}\cdot\boldsymbol{\nabla}\rho + \sum_{q=n,p}\boldsymbol{J}_q\cdot\boldsymbol{\nabla}\rho_q\right).\end{aligned} \tag{A3}$$

Brussels-Montreal (BSk) functional

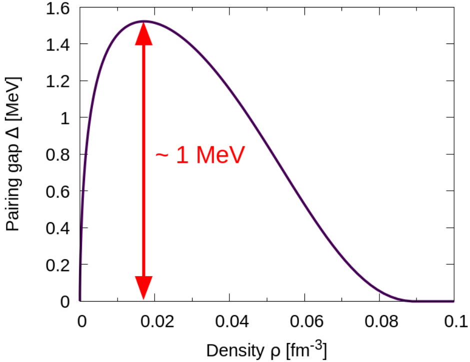
Experimental data

- atomic masses
- nuclear charge radii
- symmetry energy
- incompressibility

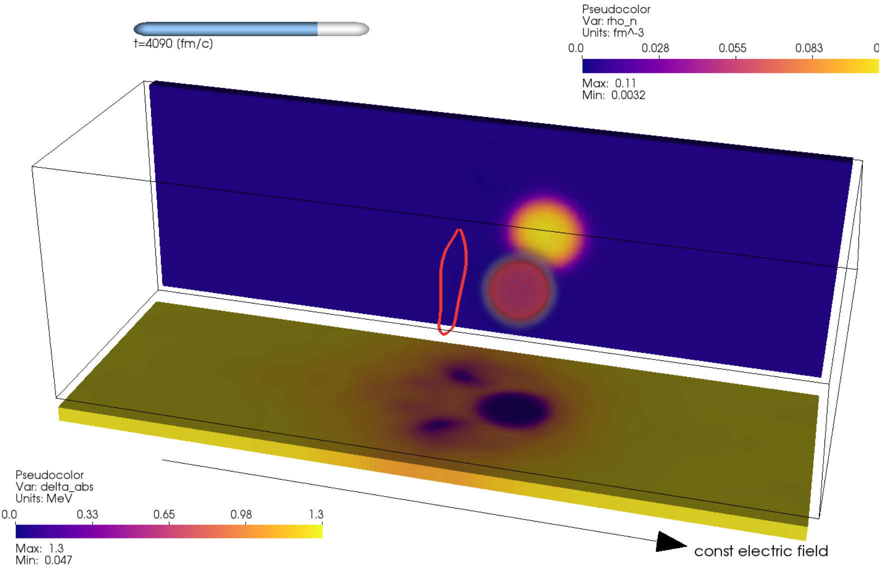
N-body calculations

- EoS of pure neutron matter
- $^1S_0$ pairing gaps in nuclear matter
- effective masses in nuclear matter

Chamel et al., Phys. Rev. C **80**, 065804 (2009)
Goriely et al., Phys. Rev. Lett. **102**, 152503 (2009)
Goriely et al., Phys. Rev. C **93**, 034337 (2016)



$$\varepsilon(\rho_q, \vec{\nabla}\rho_q, \nu_q, \tau_q, \boldsymbol{j}_q)$$



t=4090 (fm/c)
Pseudocolor
Var: rho_n
Units: fm^-3
0.0
0.028
0.055
0.083
Max: 0.11
Min: 0.0032
Pseudocolor
Var: delta_abs
Units: MeV
0.0
0.33
0.65
0.98
1.3
Max: 1.3
Min: 0.047
const electric field

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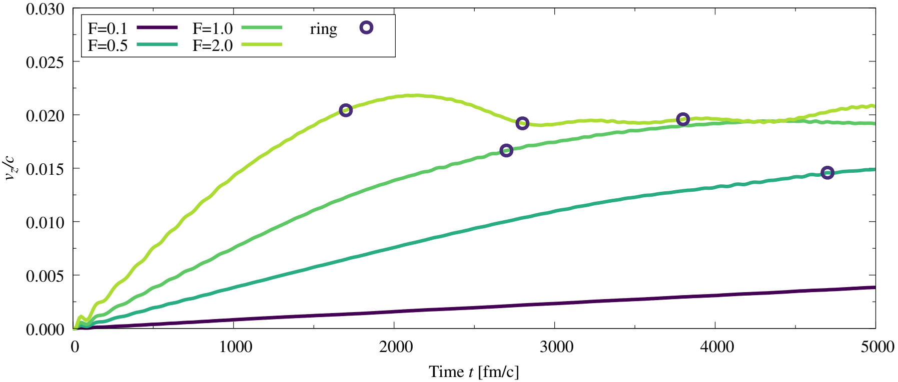
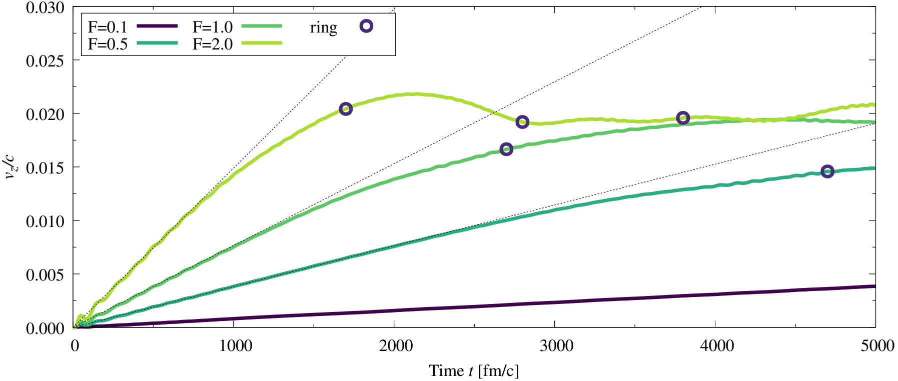
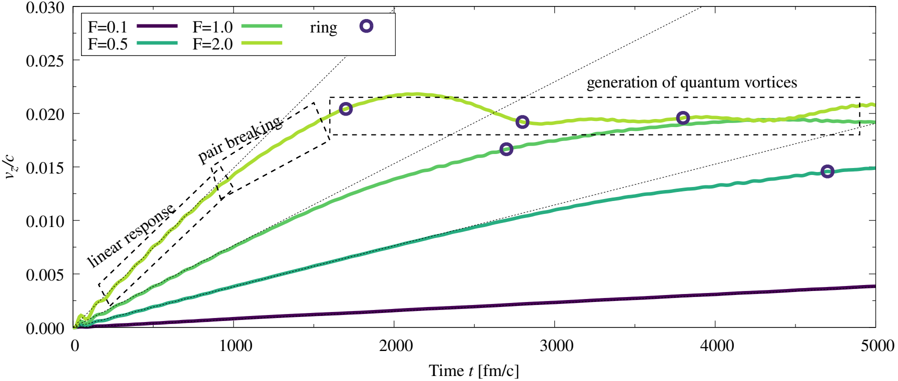

F=0.1
F=0.5
F=1.0
F=2.0
ring
0.030
0.025
0.020
0.015
0.010
0.005
0.000
v_z/c
0
1000
2000
3000
4000
5000
Time t [fm/c]



$$v_z = a_z t$$

$$M_{eff}^{(d)} = \frac{F}{a_z}$$



$$v_z = a_z t$$

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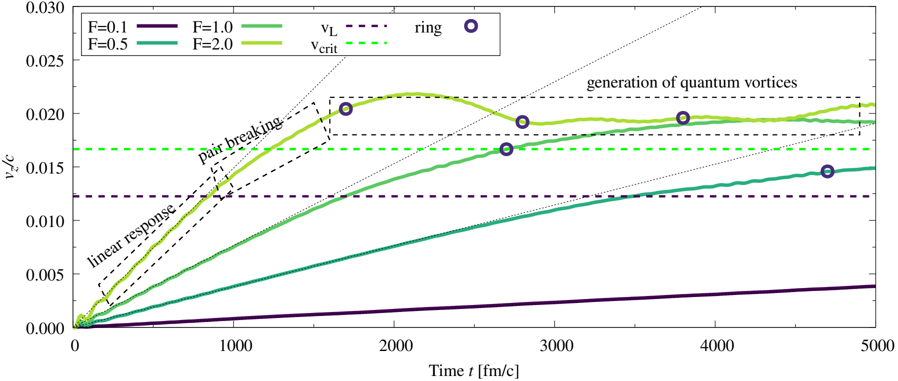
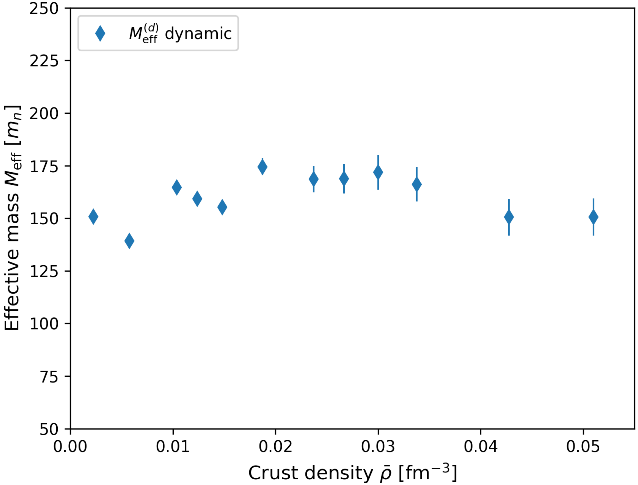


$$v_z = a_z t$$

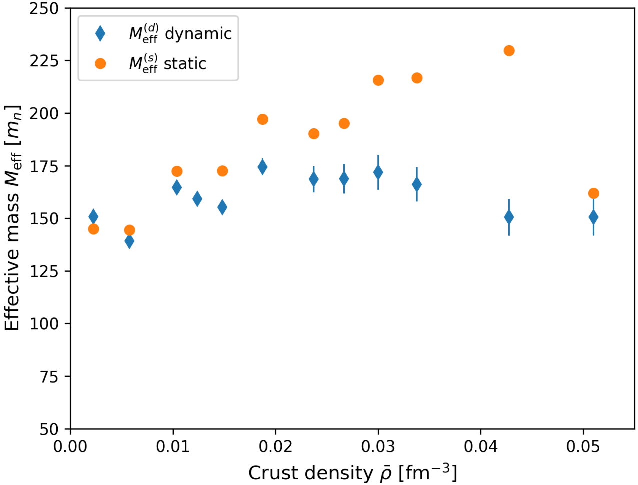
$$M_{eff}^{(d)} = \frac{F}{a_z}$$

$$v_L = \frac{\Delta}{\hbar k_F}$$

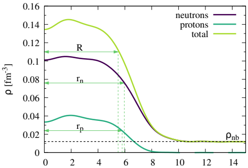
$$v_{\mathrm{crit}} = \frac{e}{2}\frac{\Delta}{\hbar k_F}$$



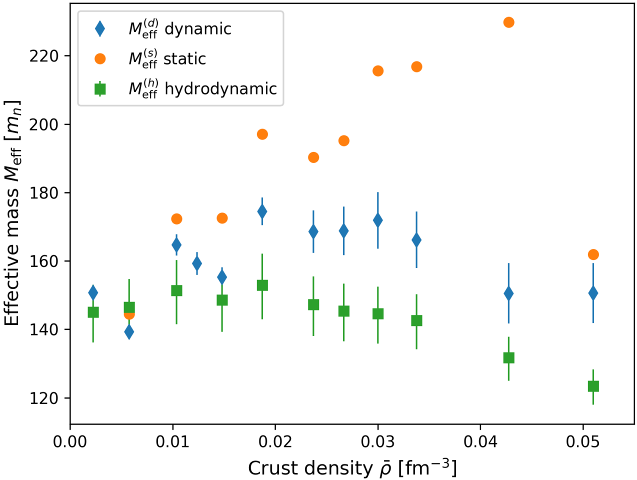
$M_{\mathrm{eff}}^{(d)}$ dynamic
Effective mass M_{eff} [m_n]
Crust density $\bar{\rho}$ [fm^{-3}]
250
225
200
175
150
125
100
75
50
0.00
0.01
0.02
0.03
0.04
0.05



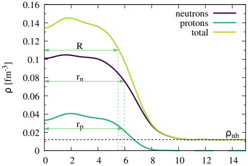
$M_{\rm eff}^{(d)}$ dynamic
$M_{\rm eff}^{(s)}$ static
Effective mass $M_{\rm eff}$ [m_n]
Crust density $\bar{\rho}$ [fm^{-3}]



neutrons
protons
total
R
r_n
r_p
ρ_{nb}
ρ [fm^{-3}]

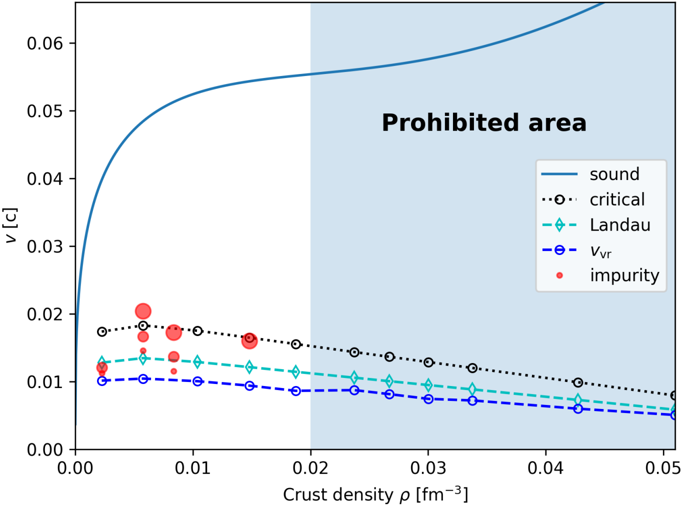


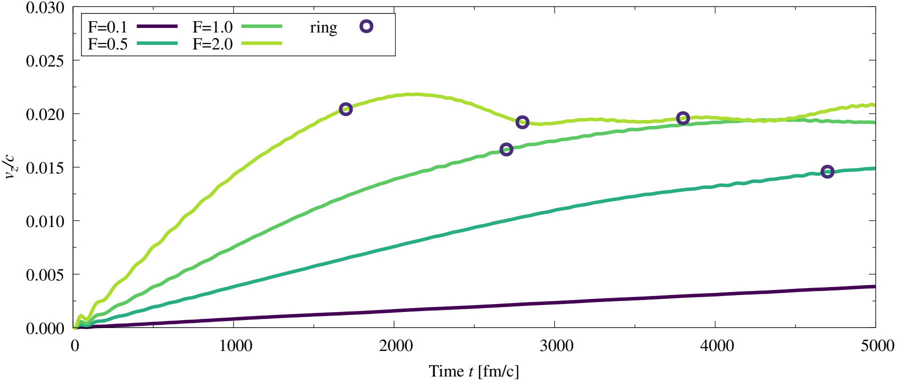
$$M_h = \frac{4}{3}\pi R^3 M_n \frac{(\rho_{\rm in} - \rho_{\rm out})^2}{\rho_{\rm in} + 2\rho_{\rm out}}.$$

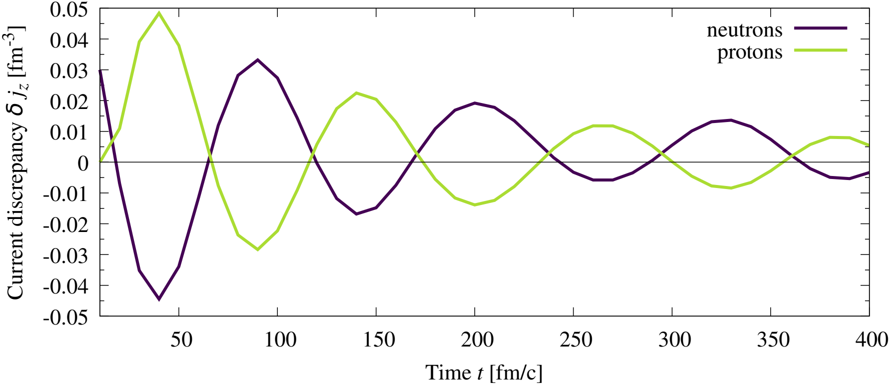


P. Magierski, Int. J. Mod. Phys. E 13 , 371-374 (2004)

$$v_{vr} = \frac{1}{2\pi R}\frac{\hbar c}{M_n c^2}\left(\ln\frac{8R}{a_{core}} - \alpha\right)$$



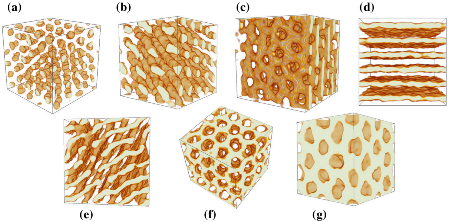

0.030
0.025
0.020
0.015
0.010
0.005
0.000
v_z/c
0
1000
2000
3000
4000
5000
Time t [fm/c]
F=0.1
F=0.5
F=1.0
F=2.0
ring



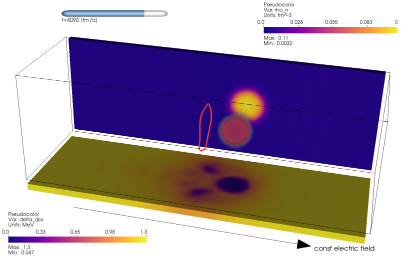
neutrons
protons
Current discrepancy δj_z [fm^{-3}]
Time t [fm/c]
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
50
100
150
200
250
300
350
400

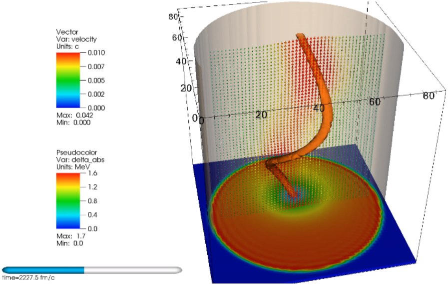
Outlook

- ★ dynamics
- ★ impurities
- ★ nuclear pasta
- ★ vortex-nucleus interaction
- ★ polarized systems

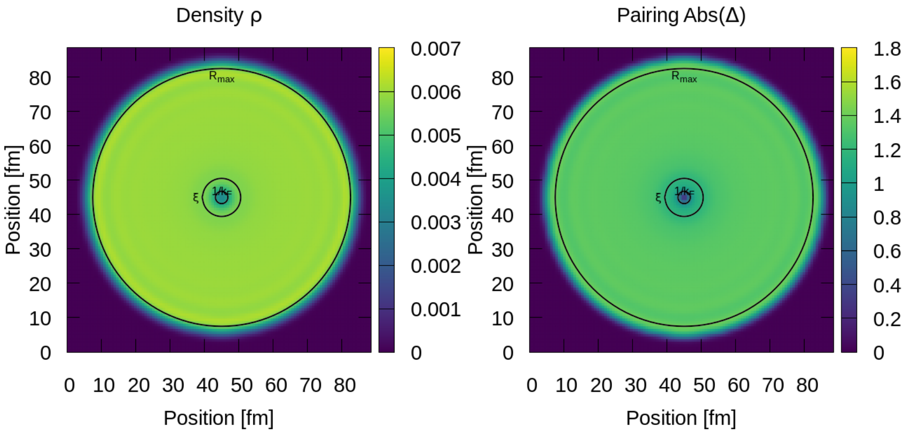


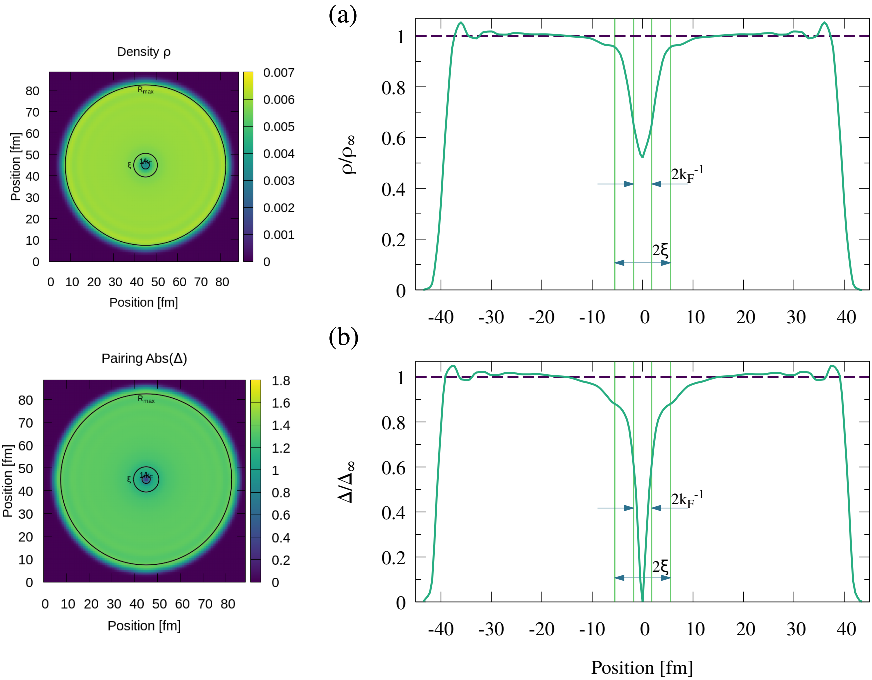
Caplan, M. E., and C. J. Horowitz. 2017. "Colloquium: Astromaterial Science and Nuclear Pasta." Reviews of Modern Physics 89 (4): 041002.



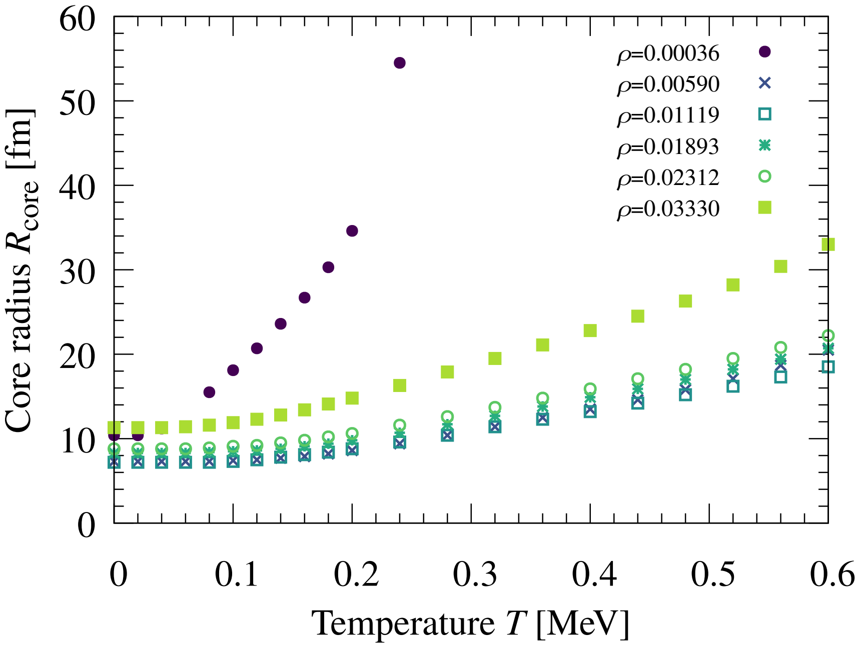


Density: ρ=0.00590 [fm^{-3}] Δ=1.33394 [MeV]



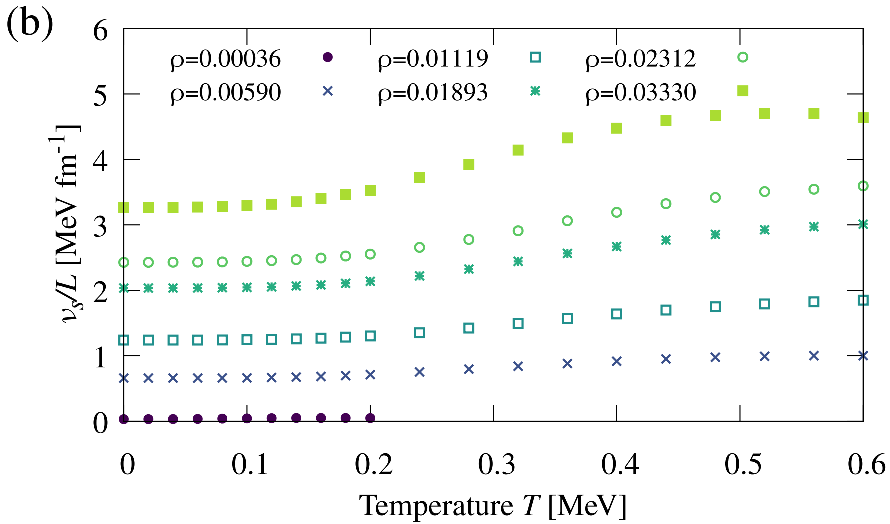


Density ρ
Pairing Abs(Δ)
Position [fm]
(a)
(b)
ρ/ρ∞
Δ/Δ∞
2kF-1
2ξ
Rmax
ξ
1/kF



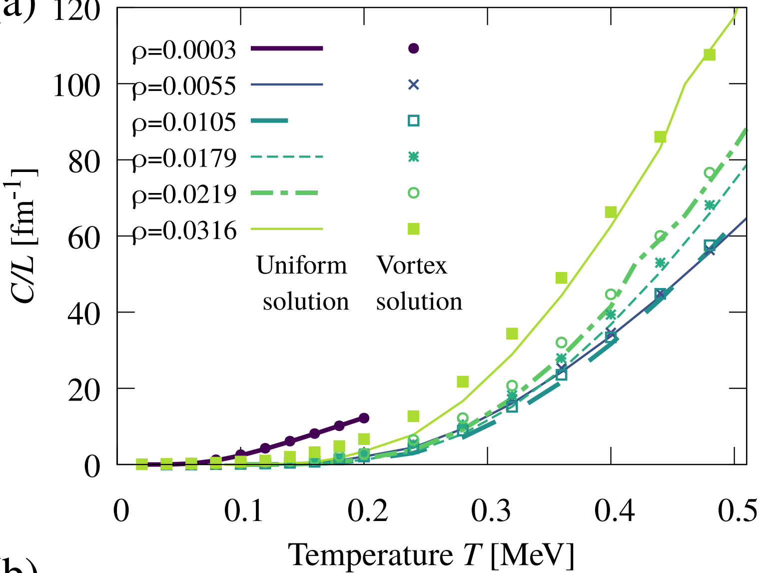
60
50
40
30
20
10
0
Core radius R_{core} [fm]
0
0.1
0.2
0.3
0.4
0.5
0.6
Temperature T [MeV]
ρ=0.00036
ρ=0.00590
ρ=0.01119
ρ=0.01893
ρ=0.02312
ρ=0.03330

Tension


(b)
ρ=0.00036
ρ=0.01119
ρ=0.02312
ρ=0.00590
ρ=0.01893
ρ=0.03330
ν_s/L [MeV fm^{-1}]
Temperature T [MeV]
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6

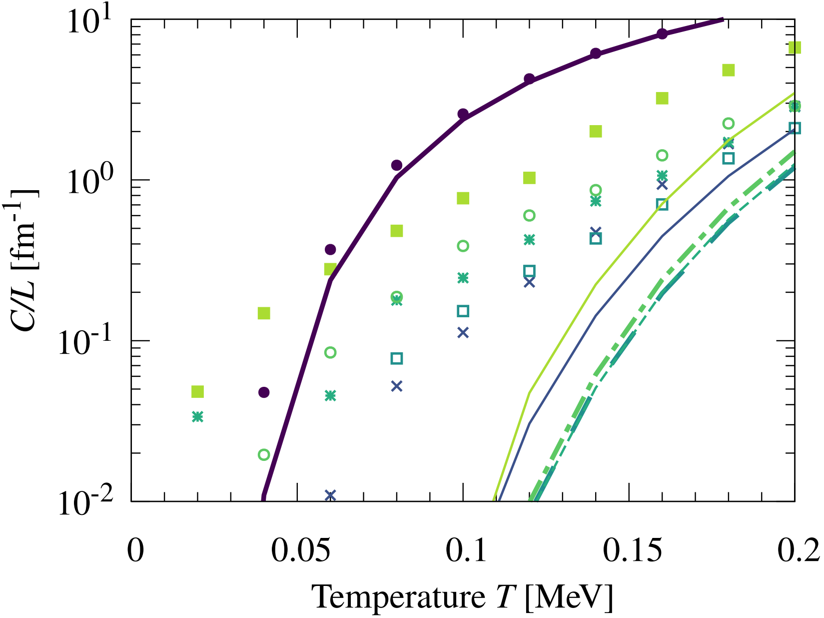
Heat capacity

(a)

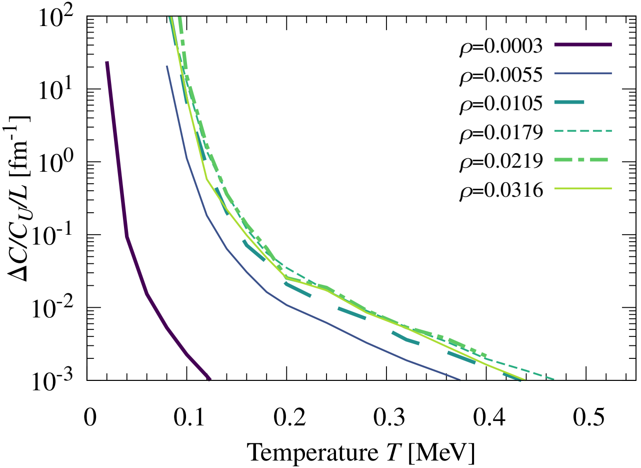


(b)

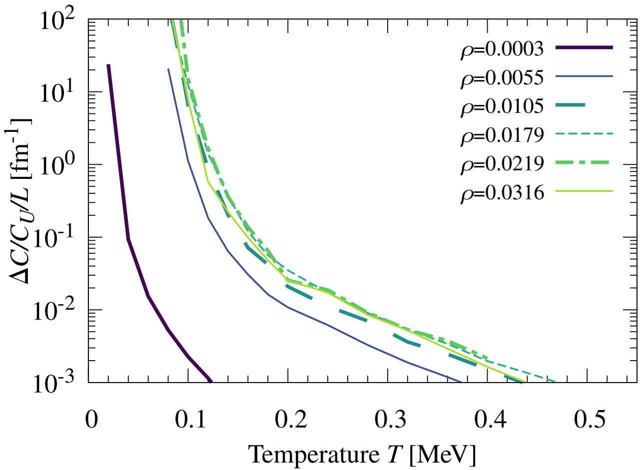
Heat capacity



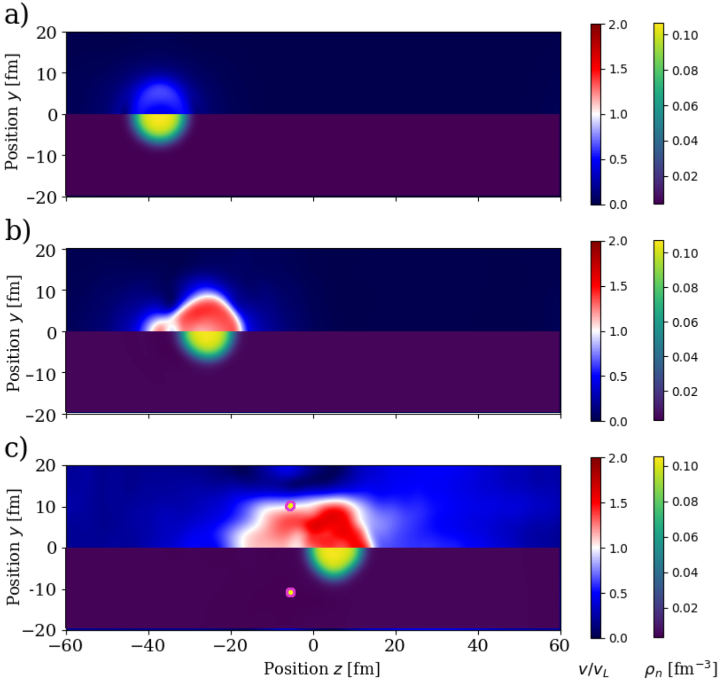
Heat capacity

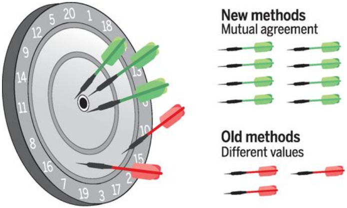


Heat capacity



$$\frac{\Delta C_V^{flow}}{L} = \frac{\hbar^2}{24M\Delta}\pi \ln\left(\frac{R_{out}}{R_{in}}\right)\frac{\mu}{\Delta}\left(\left(\frac{\Delta}{T}\right)^2 - 4\left(\frac{\Delta}{T}\right) + 2\right) C_V^{uniform}$$


a)
b)
c)
Position y [fm]
Position z [fm]
v/v_L
ρ_n [fm^{-3}]



Scorecard

	0.3	0.3	0.6	1.0	0.9	0.3	1.5	0.6	0.9	0.4	1.0	0.4	0.4	6.3	13.5	1.1	2.1	0.7	1.4
0.3		0.1	0.5	0.9	0.8	0.2	1.5	0.6	0.8	0.4	1.0	0.5	0.3	6.3	13.4	1.1	2.1	0.7	1.4
0.3	0.1		0.5	0.9	0.8	0.2	1.5	0.6	0.8	0.4	0.9	0.5	0.3	6.3	13.4	1.1	2.1	0.7	1.4
0.6	0.5	0.5		0.8	0.6	0.4	1.5	0.6	0.8	0.6	1.0	0.7	0.5	6.3	13.2	1.0	1.9	0.6	1.3
1.0	0.9	0.9	0.8		0.9	0.9	1.8	0.9	1.3	1.0	1.4	1.0	0.9	6.4	13.0	1.2	1.8	1.0	1.6
0.9	0.8	0.8	0.6	0.9		0.8	1.7	0.7	1.1	0.8	1.3	1.0	0.8	6.5	13.2	1.1	1.8	0.8	1.5
0.3	0.2	0.2	0.4	0.9	0.8		1.5	0.5	0.8	0.3	1.0	0.5	0.3	6.2	13.4	1.0	2.0	0.6	1.4

Lejaeghere, Kurt, et al. "Reproducibility in density functional theory calculations of solids." Science 351, 6280 (2016)