CRITICAL PARAMETERS OF CONSISTENT RELATIVISTIC MEAN-FIELD MODELS

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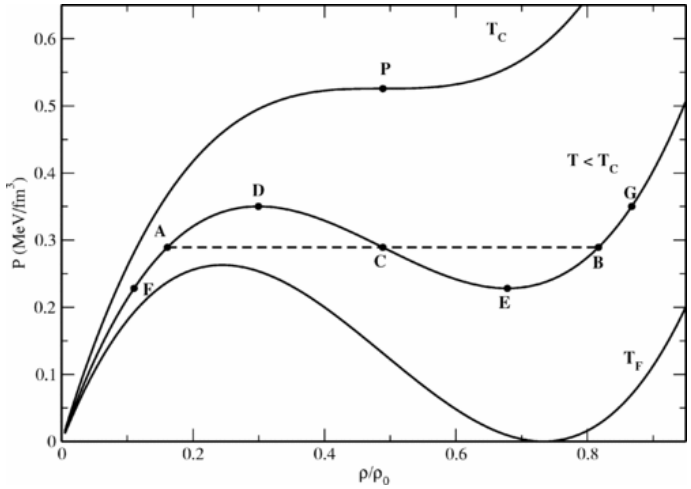
Outline

- Introduction
- Choice of models
- Results
  - Critical parameters and model dependence in the liquid phase
  - Comparison with experimental data
  - Correlations
- Summary

Introduction

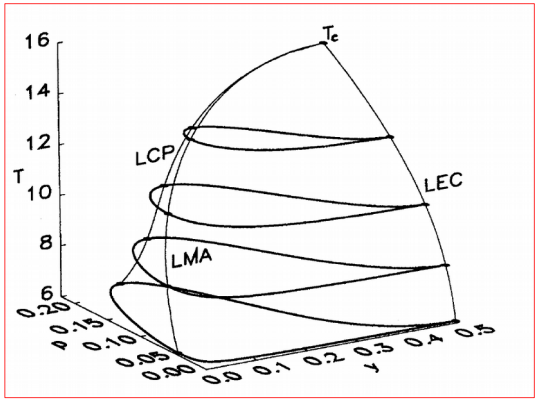
- The understanding of nuclear matter properties is of fundamental importance as a guide towards more specific subjects, such as nuclear and hadron spectroscopy, heavy-ion collisions, nuclear multifragmentation, caloric curves,…
- At finite temperatures → relativistic mean-field models (RMF) → phase transitions.
- RMF models share the prediction that a liquid - gas phase transition will occur for nuclear matter at a finite temperature ($T < 20$ MeV) and finite density ($\rho < 0.1$ fm^{-3}).
- Qualitatively, the isotherms of these RMF models typically show a van der Waals-like behavior, where liquid and gaseous phases can coexist.



J. B. Silva, A. Delfino, J. S. Sá Martins, S. Moss de Oliveira, and C. E. Cordeiro, Phys. Rev. C **69**, 024606 (2004).

Introduction

- Phase coexistence boundary in a pressure-temperature-proton fraction plane.



H. Müller and B. D. Serot, Phys. Rev. C **52**, 2072 (1995).

- The instability region decreases with the increase of the temperature up to a certain *critical temperature*, which is related to a *critical pressure* and *critical density*.

S. S. Avancini, L. Brito, P. Chomaz, D. P. Menezes, and C. Providência, Phys. Rev. C **74**, 024317 (2006).

- Critical parameters ⟶ model dependent.

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Choice of models

- Based on:

  M. Dutra, O. Lourenço, S. S. Avancini, B. V. Carlson, A. Delfino, D. P. Menezes, C. Providência, S. Typel, and J. R. Stone, Phys. Rev. C **90**, 055203 (2014).

- A set of constraints on properties of nuclear matter was formed and the performance of 263 relativistic mean-field (RMF) models parametrizations was assessed.

- These RMF parametrizations had their bulk and thermodynamical quantities compared to respective theoretical/experimental data from:

  - symmetric nuclear matter (SNM);
  - pure neutron matter (PNM);
  - and a mixture of both, namely, symmetry energy and its slope evaluated at the saturation density ρ_0, and the ratio of the symmetry energy at $\rho_0/2$ to its value at ρ_0 (MIX).

Choice of models

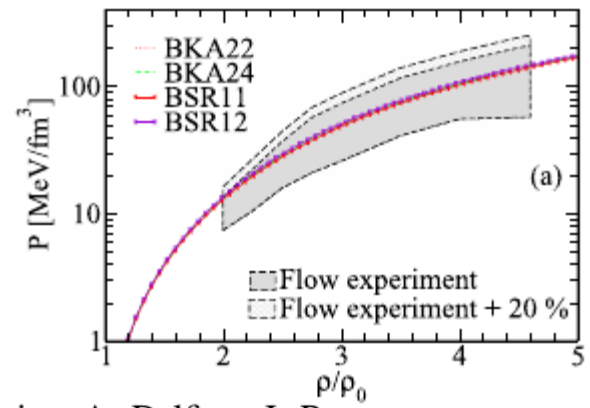
Constraint	Quantity	Density region	Range of constraint
SM1	K_0	at ρ_0	190–270 MeV
SM3a	$P(\rho)$	$2 < \frac{\rho}{\rho_0} < 5$	Band region
SM4	$P(\rho)$	$1.2 < \frac{\rho}{\rho_0} < 2.2$	Band region
PNM1	$\mathcal{E}_{\rm PNM}/\rho$	$0.017 < \frac{\rho}{\rho_0} < 0.108$	Band region
MIX1a	J	at ρ_0	25–35 MeV
MIX2a	L_0	at ρ_0	25–115 MeV
MIX4	$\frac{\mathcal{S}(\rho_0/2)}{J}$	at ρ_0 and $\rho_0/2$	0.57–0.86

SM1:

E. Khan, J. Margueron, and I. Vidaña, Phys. Rev. Lett. **109**, 092501 (2012).
E. Khan and J. Margueron, Phys. Rev. C **88**, 034319 (2013).

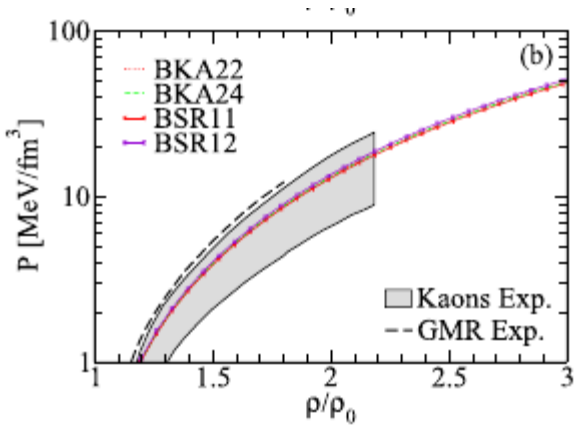
SM3a:

P. Danielewicz, R. Lacey, and W. G. Lynch, Science **298**, 1592 (2002).



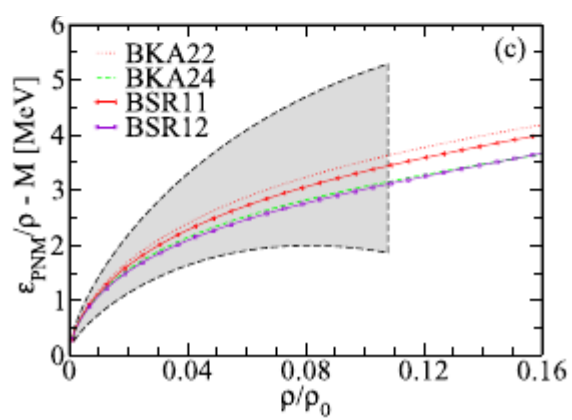
SM4:

W. G. Lynch, M. B. Tsang, Y. Zhang, P. Danielewicz, M. Famiano, Z. Li, and A. W. Steiner, Prog. Part. Nucl. Phys. **62**, 427 (2009).



PNM1:

M. Dutra, O. Lourenço, J. S. Sá Martins, A. Delfino, J. R. Stone, and P. D. Stevenson, Phys. Rev. C **85**, 035201 (2012).



$$K_0 = 9\left(\frac{\partial P}{\partial \rho}\right)_{\rho=\rho_0, y=1/2}$$

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MIX4:

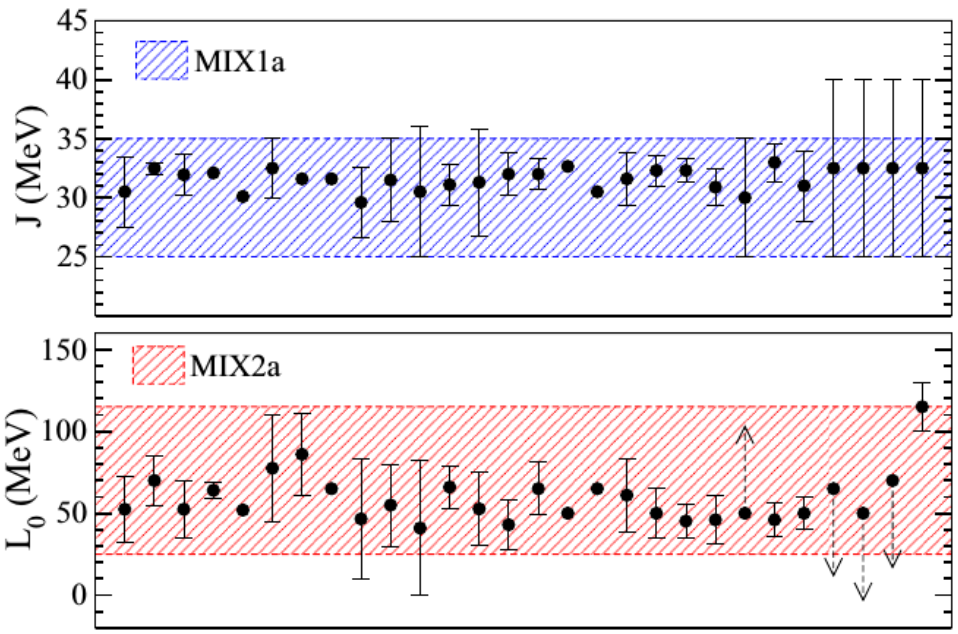
P. Danielewicz, Nucl. Phys. A **727**, 233 (2003).

$$\mathcal{S}(\rho) = \frac{1}{8}\frac{\partial^2(\mathcal{E}/\rho)}{\partial y^2}\bigg|_{\rho,y=1/2}$$

$$J = \mathcal{S}(\rho_0) \quad \text{(symmetry energy at } \rho = \rho_0\text{)}$$

$$L_0 = 3\rho_0\left(\frac{\partial \mathcal{S}}{\partial \rho}\right)_{\rho=\rho_0}$$

MIX1a and MIX2a:



Comparison between the limits used in this constraints, and those from 28 different experimental/observational data collected in B.-A. Li and X. Han, Phys. Lett. B **727**, 276 (2013): include analyses of isospin diffusion, neutron skins, pygmy dipole resonances, and decays, transverse flow, the mass-radius relation and torsional crust oscillations of neutron stars.

Choice of models

- The analysis performed pointed out to only **35** parametrizations were approved.

  (i) 30 Consistent RMF (CRMF) parametrizations:

  - **BKA20, BKA22, BKA24, BSR8, BSR9, BSR10, BSR11, BSR12, BSR15, BSR16, BSR17, BSR18, BSR19, BSR20, FSU-III, FSU-IV, FSUGold, FSUGold4, FSUGZ03, FSUGZ06, G2*, IU-FSU, Z271s2, Z271s3, Z271s4, Z271s5, Z271s6, Z271v4, Z271v5,** and **Z271v6**.

  - The Lagrangian density comprises nonlinear σ and ω terms and cross terms involving these fields.

$$
\begin{aligned}
\mathcal{L}_{\rm NL} &= \overline{\psi}(i\gamma^\mu\partial_\mu - M)\psi + g_\sigma\sigma\overline{\psi}\psi - g_\omega\overline{\psi}\gamma^\mu\omega_\mu\psi - \frac{g_\rho}{2}\overline{\psi}\gamma^\mu\vec{\rho}_\mu\vec{\tau}\psi + \frac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2) \\
&- \frac{A}{3}\sigma^3 - \frac{B}{4}\sigma^4 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{C}{4}(g_\omega^2\omega_\mu\omega^\mu)^2 - \frac{1}{4}\vec{B}^{\mu\nu}\vec{B}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu \\
&+ \frac{1}{2}\alpha_3' g_\omega^2 g_\rho^2\omega_\mu\omega^\mu\vec{\rho}_\mu\vec{\rho}^\mu + g_\sigma g_\omega^2\sigma\omega_\mu\omega^\mu\left(\alpha_1 + \frac{1}{2}\alpha_1' g_\sigma\sigma\right) + g_\sigma g_\rho^2\sigma\vec{\rho}_\mu\vec{\rho}^\mu\left(\alpha_2 + \frac{1}{2}\alpha_2' g_\sigma\sigma\right),
\end{aligned}
$$

with $F_{\mu\nu} = \partial_\nu\omega_\mu - \partial_\mu\omega_\nu$ and $\vec{B}_{\mu\nu} = \partial_\nu\vec{\rho}_\mu - \partial_\mu\vec{\rho}_\nu$.

Choice of models

(ii) 2 CRMF parametrizations → density dependent: **DD-F** and **TW99**

(iii) 2 CRMF parametrizations → density dependent + δ meson: **DDHδ** and **DD-MEδ**

$$\begin{aligned}\mathcal{L}_{\rm DD} &= \overline{\psi}(i\gamma^\mu\partial_\mu - M)\psi + \Gamma_\sigma(\rho)\sigma\overline{\psi}\psi - \Gamma_\omega(\rho)\overline{\psi}\gamma^\mu\omega_\mu\psi - \frac{\Gamma_\rho(\rho)}{2}\overline{\psi}\gamma^\mu\vec{\rho}_\mu\vec{\tau}\psi + \Gamma_\delta(\rho)\overline{\psi}\vec{\delta}\vec{\tau}\psi \\ &- \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2) + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{B}^{\mu\nu}\vec{B}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu \\ &+ \frac{1}{2}(\partial^\mu\vec{\delta}\partial_\mu\vec{\delta} - m_\delta^2\vec{\delta}^2),\end{aligned}$$

where

$$\Gamma_i(\rho) = \Gamma_i(\rho_0)f_i(x); \quad f_i(x) = a_i\frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}, \quad \text{for } i=\sigma,\omega, \text{ and } x=\rho/\rho_0.$$

(iv) 1 CRMF parametrization → point-coupling: **FA3**

→ we remark that, due to its very particular behavior in the high-density regime; namely, a fall in the curve pε near ε = 4.1 fm^{-4} (p is the pressure and ε is the energy density), it was not possible to generate a mass radius curve indicating a maximum mass.

M. Dutra, O. Lourenço, and D. P. Menezes, Phys. Rev. C **93**, 025806 (2016); **94**, 049901(E) (2016).

→ Therefore, we have discarded such a model from our analysis.

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Critical parameters and model dependence in the liquid phase

- Equation of state for NL (SNM):

$$P_{\rm NL} = -\frac{1}{2}m_\sigma^2\sigma^2 - \frac{A}{3}\sigma^3 - \frac{B}{4}\sigma^4 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{C}{4}(g_\omega^2\omega_0^2)^2 + g_\sigma g_\omega^2\sigma\omega_0^2\left(\alpha_1 + \frac{1}{2}\alpha_1' g_\sigma\sigma\right)$$
$$+\frac{\gamma}{6\pi^2}\int_0^\infty \frac{dk\,k^4}{(k^2+M^{*2})^{1/2}}\left[n(k,T,\mu^*) + \bar{n}(k,T,\mu^*)\right],$$

where
$$n(k,T,\mu^*) = \frac{1}{e^{(E^*-\mu^*)/T}+1}, \quad \text{and}$$
$$\bar{n}(k,T,\mu^*) = \frac{1}{e^{(E^*+\mu^*)/T}+1}.$$

$$E^* = (k^2+M^{*2})^{1/2},\ M^* = M - g_\sigma\sigma,\ \text{and}\ \mu^* = \mu - g_\omega\omega_0,$$

steps indicating in R. J. Furnstahl and B. D. Serot, Phys. Rev. C **41**, 262 (1990).

- By using the mean-field approximation we get:

$$\begin{aligned} m_\sigma^2\sigma &= g_\sigma\rho_s - A\sigma^2 - B\sigma^3 + g_\sigma g_\omega^2\omega_0^2(\alpha_1 + \alpha_1' g_\sigma\sigma) \\ m_\omega^2\omega_0 &= g_\omega\rho - Cg_\omega(g_\omega\omega_0)^3 - g_\sigma g_\omega^2\sigma\omega_0(2\alpha_1 + \alpha_1' g_\sigma\sigma), \end{aligned}$$

with
$$\rho = \frac{\gamma}{2\pi^2}\int_0^\infty dk\,k^2\left[n(k,T,\mu^*) - \bar{n}(k,T,\mu^*)\right],$$
$$\rho_s = \frac{\gamma}{2\pi^2}\int_0^\infty \frac{dk\,M^*k^2}{(k^2+M^{*2})^{1/2}}\left[n(k,T,\mu^*) + \bar{n}(k,T,\mu^*)\right].$$

Critical parameters and model dependence in the liquid phase

- Equation of state for DD and DD + δ (SNM):

$$P_{\rm DD} = \rho\Sigma_R(\rho) - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{\gamma}{6\pi^2}\int_0^\infty \frac{dk\,k^4}{(k^2+M^{*2})^{1/2}}\left[n(k,T,\mu^*)+\bar{n}(k,T,\mu^*)\right],$$

with the rearrangement term defined as

$$\Sigma_R(\rho) = \frac{\partial\Gamma_\omega}{\partial\rho}\omega_0\rho - \frac{\partial\Gamma_\sigma}{\partial\rho}\sigma\rho_s.$$

The mean fields σ and ω_0 are given by

$$\sigma = \frac{\Gamma_\sigma(\rho)}{m_\sigma^2}\rho_s, \quad \text{and} \quad \omega_0 = \frac{\Gamma_\omega(\rho)}{m_\omega^2}\rho,$$

with the functional forms of ρ and ρ_s given as in the nonlinear model.

$$\rho = \frac{\gamma}{2\pi^2}\int_0^\infty dk\,k^2\left[n(k,T,\mu^*)-\bar{n}(k,T,\mu^*)\right],$$

$$\rho_s = \frac{\gamma}{2\pi^2}\int_0^\infty \frac{dk\,M^*k^2}{(k^2+M^{*2})^{1/2}}\left[n(k,T,\mu^*)+\bar{n}(k,T,\mu^*)\right].$$

$$M^* = M - \Gamma_\sigma(\rho)\sigma, \text{ and } \mu^* = \mu - \Gamma_\omega(\rho)\omega_0 - \Sigma_R(\rho).$$

Critical parameters and model dependence in the liquid phase

- In order to find the critical parameters P_c, T_c, and ρ_c we impose the following conditions:

$$P_c = P(\rho_c, T_c), \quad \left.\frac{\partial P}{\partial \rho}\right|_{\rho_c, T_c} = 0, \quad \left.\frac{\partial^2 P}{\partial \rho^2}\right|_{\rho_c, T_c} = 0$$

Critical parameters and model dependence in the liquid phase

Model	T_c (MeV)	ρ_c (fm^{-3})	P_c (MeV/fm^3)	$\frac{\rho_c}{\rho_0}$
BKA20	14.92	0.0458	0.209	0.314
BKA22	13.91	0.0442	0.178	0.300
BKA24	13.83	0.0450	0.177	0.306
BSR8	14.17	0.0440	0.185	0.300
BSR9	14.11	0.0450	0.185	0.305
BSR10	13.90	0.0439	0.176	0.297
BSR11	14.00	0.0442	0.179	0.301
BSR12	14.15	0.0448	0.185	0.304
BSR15	14.53	0.0456	0.199	0.313
BSR16	14.44	0.0454	0.196	0.311
BSR17	14.32	0.0451	0.191	0.308
BSR18	14.25	0.0451	0.189	0.309
BSR19	14.28	0.0451	0.190	0.308
BSR20	14.41	0.0464	0.197	0.318
FSU-III	14.75	0.0461	0.205	0.311
FSU-IV	14.75	0.0461	0.205	0.311
FSUGold	14.75	0.0461	0.205	0.311
FSUGold4	14.80	0.0456	0.204	0.309
FSUGZ03	14.11	0.0450	0.185	0.305
FSUGZ06	14.44	0.0454	0.196	0.311
IU-FSU	14.49	0.0457	0.196	0.295
G2*	14.38	0.0468	0.192	0.305
Z271s2	17.97	0.0509	0.303	0.343
Z271s3	17.97	0.0509	0.303	0.343
Z271s4	17.97	0.0509	0.303	0.343
Z271s5	17.97	0.0509	0.303	0.343
Z271s6	17.97	0.0509	0.303	0.343
Z271v4	17.97	0.0509	0.303	0.343
Z271v5	17.97	0.0509	0.303	0.343
Z271v6	17.97	0.0509	0.303	0.343
DD-F	15.24	0.0505	0.245	0.343
TW99	15.17	0.0509	0.241	0.332
DDHδ	15.17	0.0509	0.241	0.332
DD-MEδ	15.32	0.0491	0.235	0.323

O. Lourenço, M. Dutra, and D. P. Menezes, Phys. Rev. C**95**, 065212 (2017).

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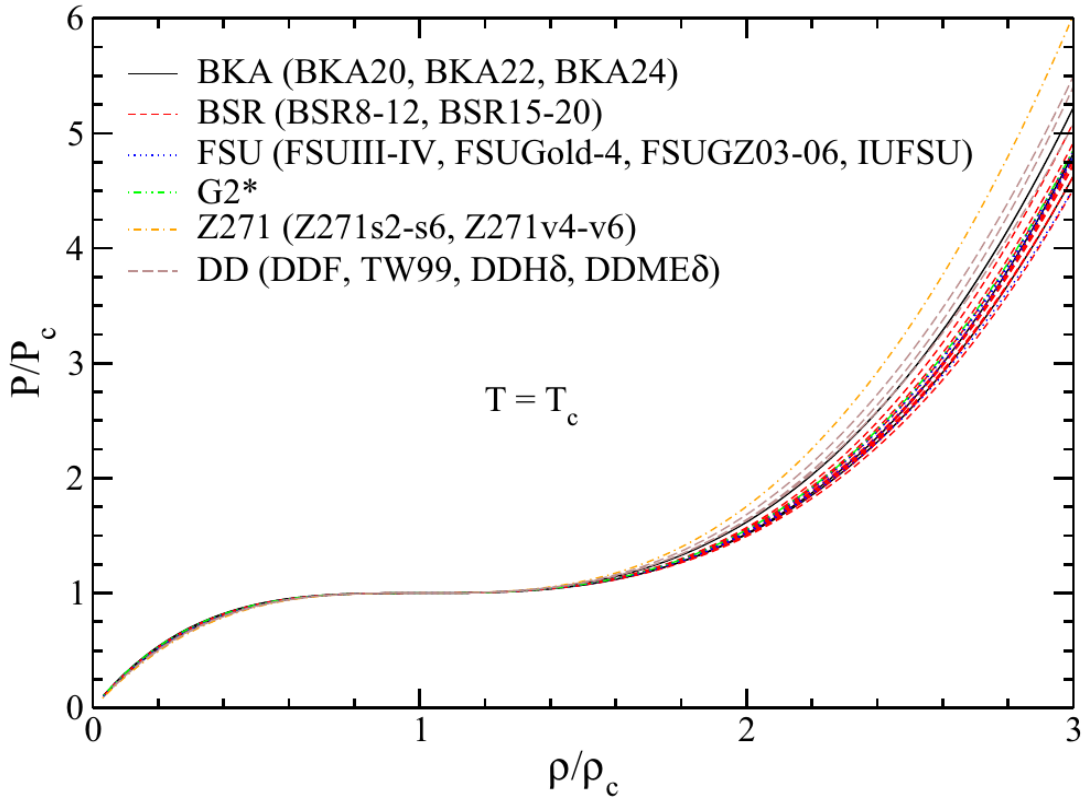

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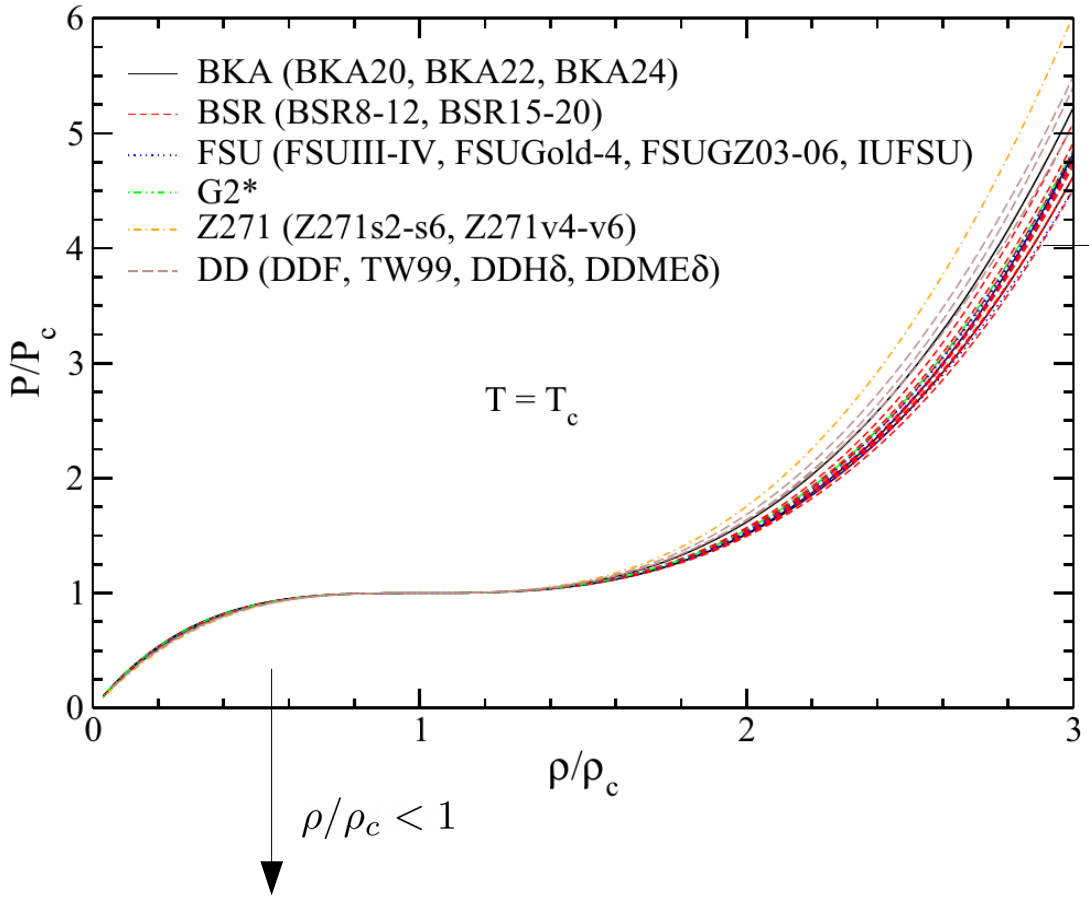

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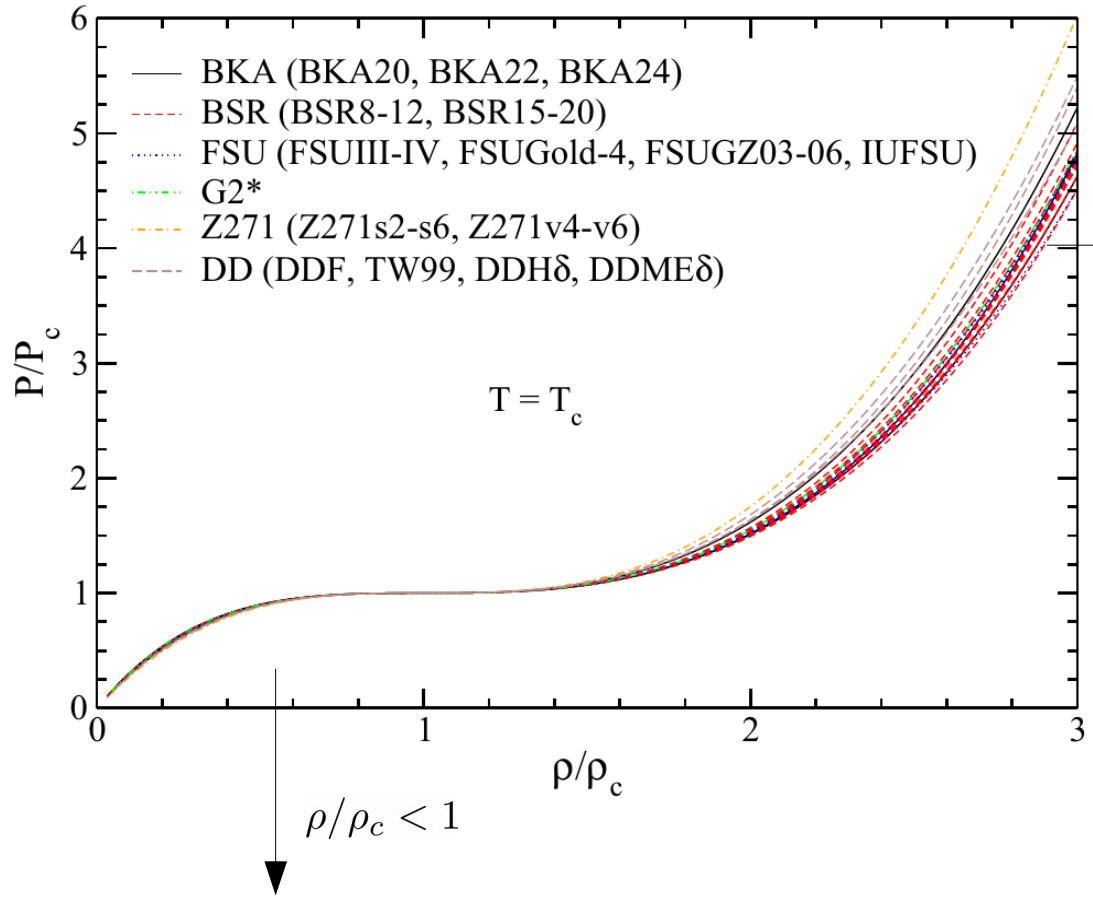
$\rho/\rho_c > 1$ → distinct from each other (liquid phase)

$\rho/\rho_c < 1$ → indistinguishable (gaseous phase)

Critical parameters and model dependence in the liquid phase



O. Lourenço, M. Dutra, and D. P. Menezes, Phys. Rev. C**95**, 065212 (2017).

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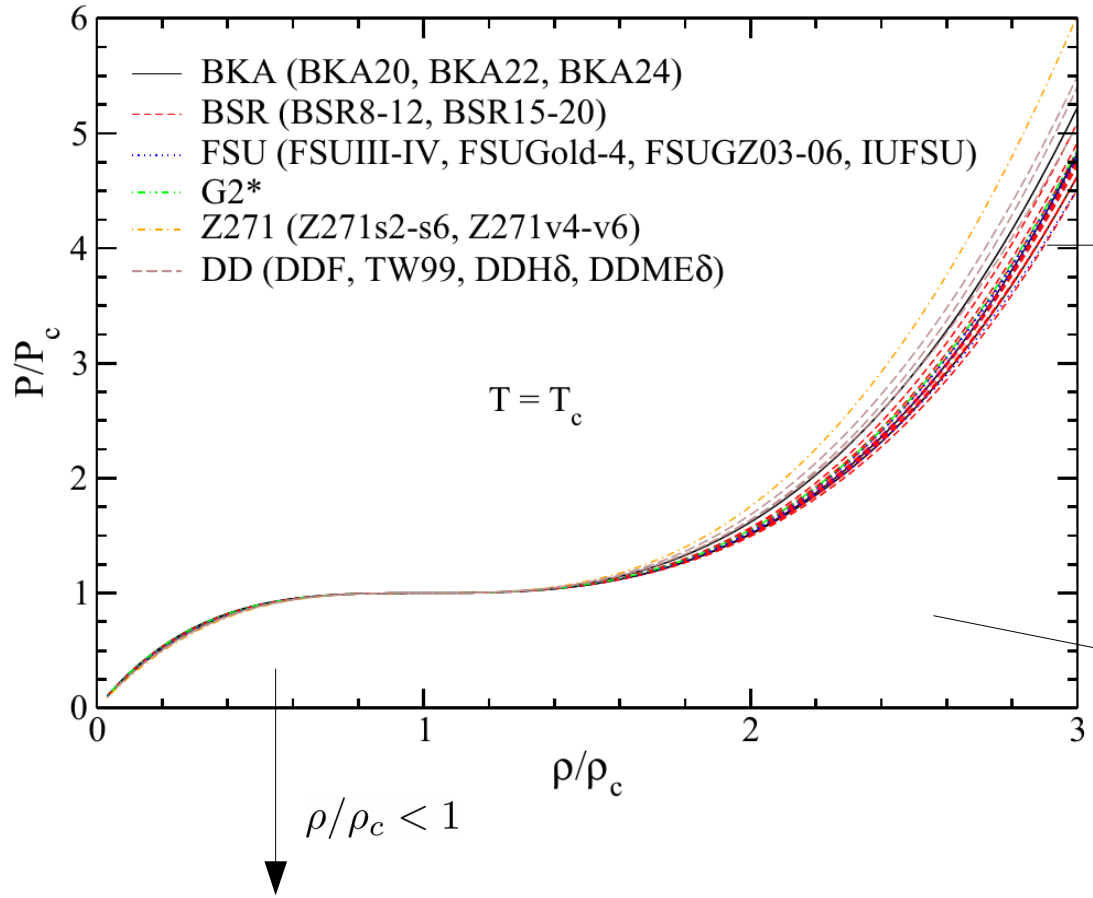
RMF models presenting only third- and fourth-order self-interactions in the scalar field σ (Boguta-Bodmer model)

J. B. Silva, O. Lourenço, A. Delfino, J. S. S. Martins, and M. Dutra, Phys. Lett. B **664**, 246 (2008).

Critical parameters and model dependence in the liquid phase



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general trend of RMF parametrizations of any kind in presenting a model dependence in the liquid phase, and a scaling in the gaseous one, at symmetric nuclear matter environment.

$\rho/\rho_c < 1$ → indistinguishable (gaseous phase)

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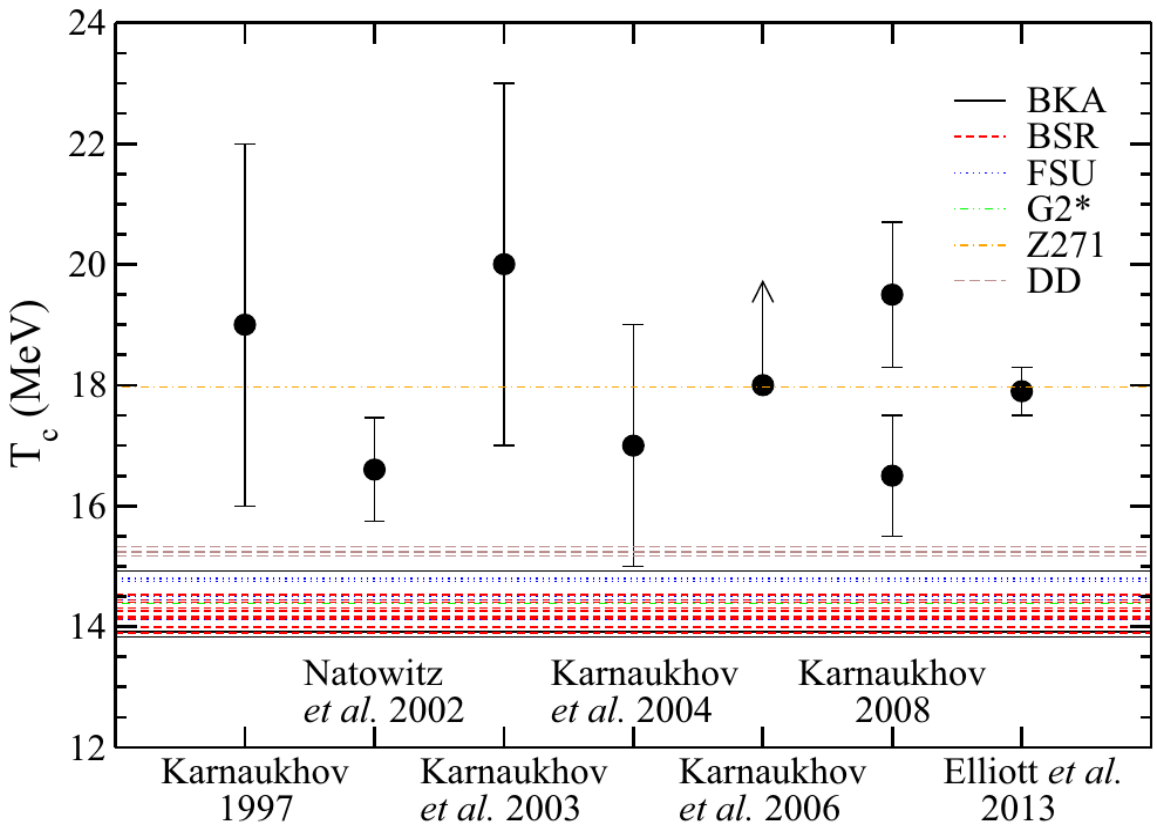
Comparison with experimental data

- Critical temperature



O. Lourenço, M. Dutra, and D. P. Menezes, Phys. Rev. C **95**, 065212 (2017).

- TW99, DD-F, DDHδ, and DD-Meδ: present T_c inside the range of

$$15 \leqslant T_c \leqslant 19 \text{ MeV}$$

- Z271Family: T_c compatible with five of the 8 experimental points, including the more recent one.

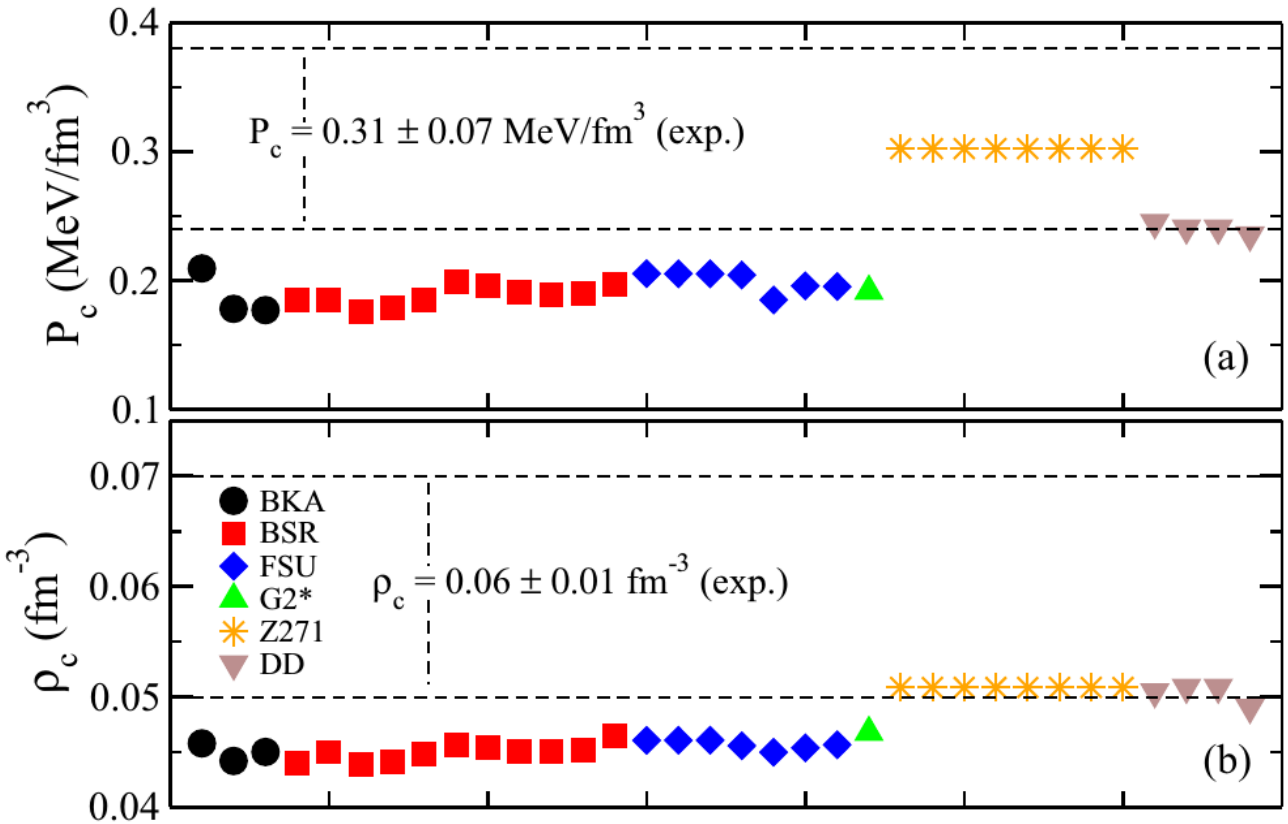
$$T_c = 17.9 \pm 0.4 \text{ MeV}$$

Comparison with experimental data

- Critical pressure and density

J. B. Elliott, P. T. Lake, L. G. Moretto, and L. Phair, Phys. Rev. C **87**, 054622 (2013).

$$P_c = 0.31 \pm 0.07\ \mathrm{MeV/fm^3}$$
$$\rho_c = 0.06 \pm 0.01\ \mathrm{fm^{-3}}$$



O. Lourenço, M. Dutra, and D. P. Menezes, Phys. Rev. C **95**, 065212 (2017).

Comparison with experimental data

- Critical pressure and density

J. B. Elliott, P. T. Lake, L. G. Moretto, and L. Phair, Phys. Rev. C **87**, 054622 (2013).

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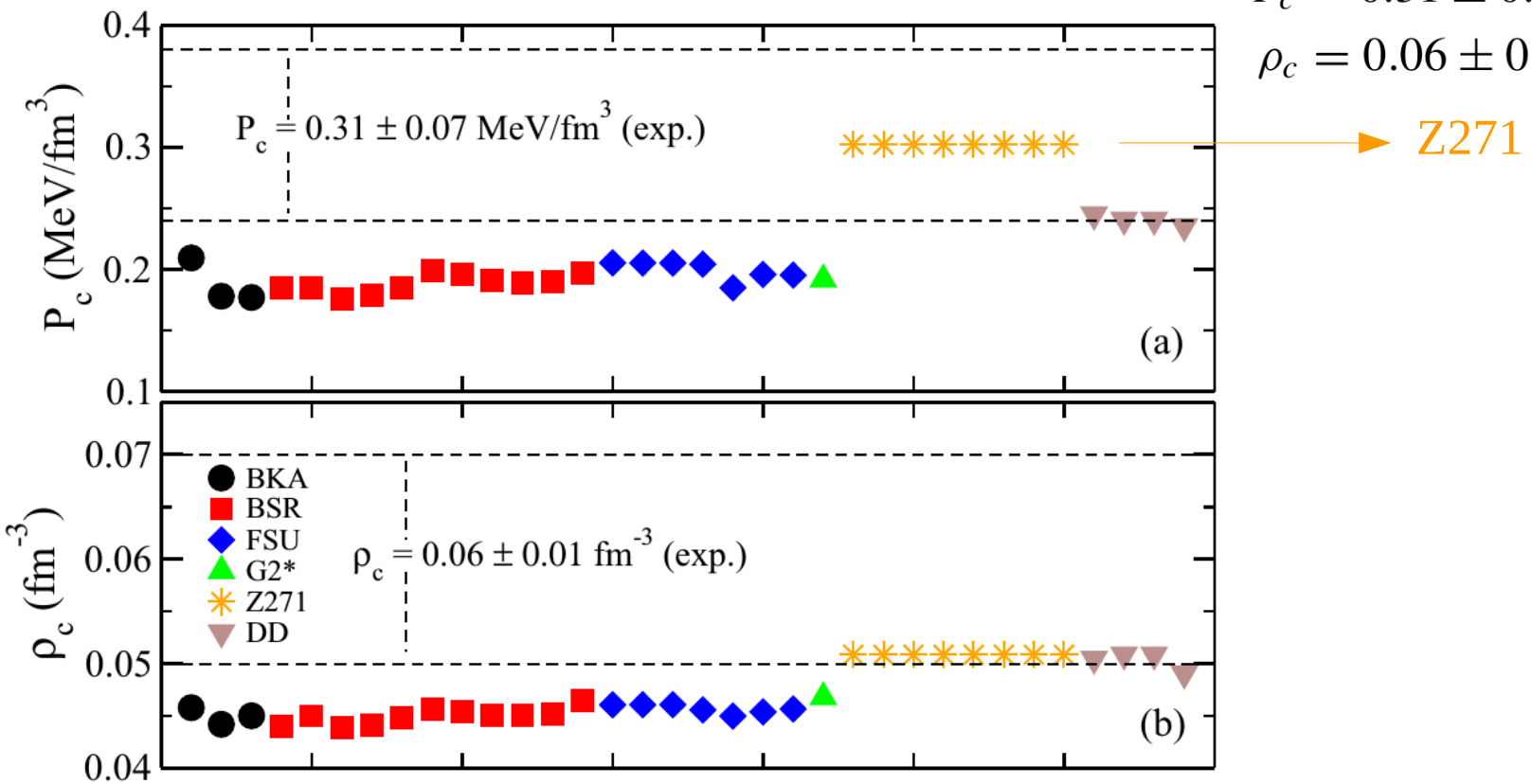

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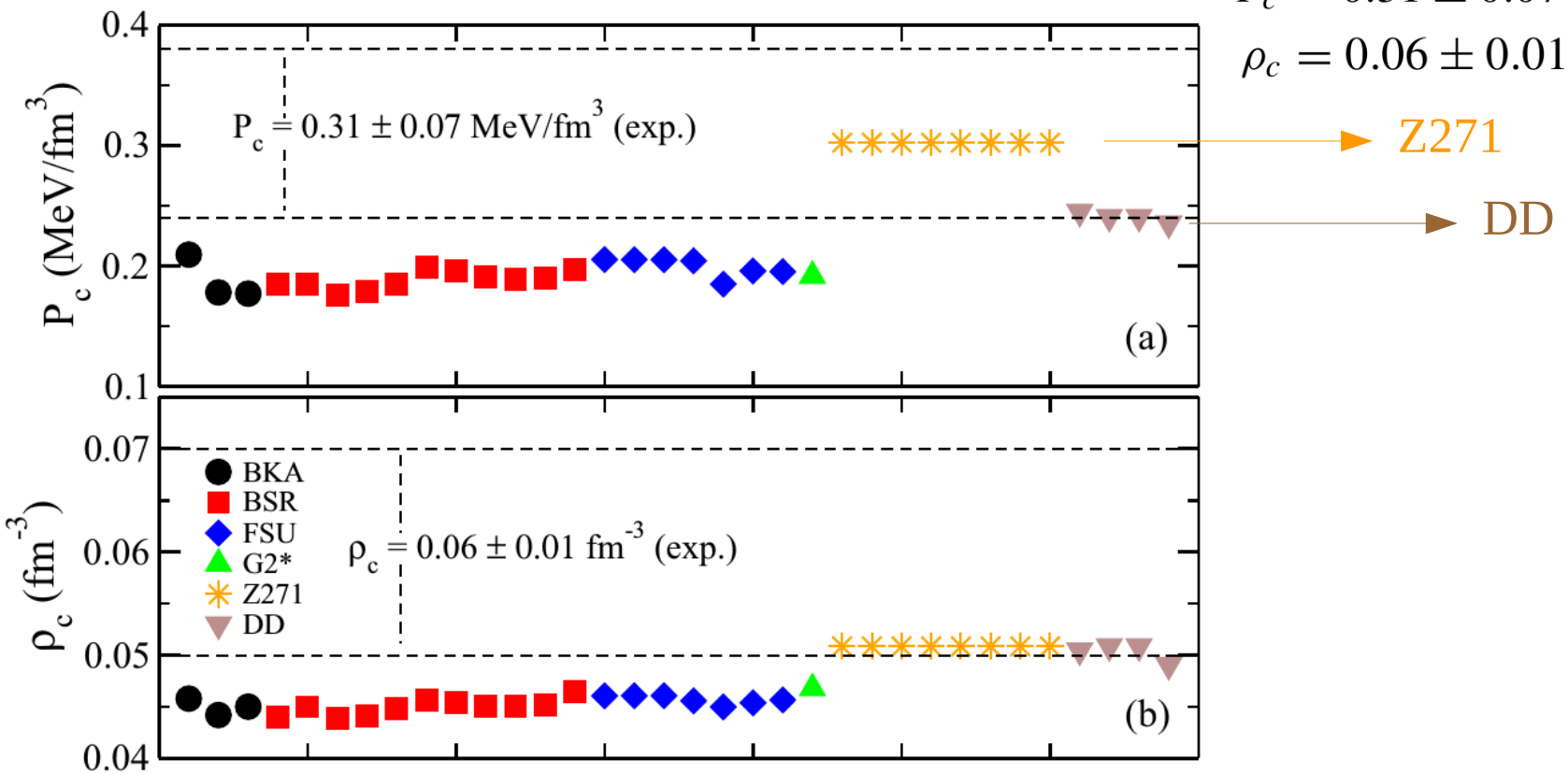

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- **Z271** Family:

$$P_{\rm NL} = -\frac{1}{2}m_\sigma^2\sigma^2 - \frac{A}{3}\sigma^3 - \frac{B}{4}\sigma^4 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{C}{4}(g_\omega^2\omega_0^2)^2 + g_\sigma g_\omega^2\sigma\omega_0^2\left(\alpha_1 + \frac{1}{2}\alpha_1' g_\sigma\sigma\right)$$
$$+\frac{\gamma}{6\pi^2}\int_0^\infty \frac{dk\,k^4}{(k^2+M^{*2})^{1/2}}\left[n(k,T,\mu^*)+\bar{n}(k,T,\mu^*)\right]$$

- α_1 and α_1' $\longrightarrow$ vanish

- $C \neq 0$ is the only constant that differs these parametrizations from those of the Boguta-Bodmer model.

Model	T_c (MeV)	ρ_c (fm^{-3})	P_c (MeV/fm^3)	$\frac{\rho_c}{\rho_0}$
⋮				
Z271s2	17.97	0.0509	0.303	0.343
Z271s3	17.97	0.0509	0.303	0.343
Z271s4	17.97	0.0509	0.303	0.343
Z271s5	17.97	0.0509	0.303	0.343
Z271s6	17.97	0.0509	0.303	0.343
Z271v4	17.97	0.0509	0.303	0.343
Z271v5	17.97	0.0509	0.303	0.343
Z271v6	17.97	0.0509	0.303	0.343
⋮				

$$T_c = 17.9 \pm 0.4 \ \text{MeV}$$
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- **DD** Family:

$$P_{\rm DD} = \rho\Sigma_R(\rho) - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{\gamma}{6\pi^2}\int_0^\infty \frac{dk\,k^4}{(k^2+M^{*2})^{1/2}}\left[n(k,T,\mu^*)+\bar{n}(k,T,\mu^*)\right],$$

$$\Sigma_R(\rho) = \frac{\partial\Gamma_\omega}{\partial\rho}\omega_0\rho - \frac{\partial\Gamma_\sigma}{\partial\rho}\sigma\rho_s, \quad \sigma = \frac{\Gamma_\sigma(\rho)}{m_\sigma^2}\rho_s, \quad \text{and} \quad \omega_0 = \frac{\Gamma_\omega(\rho)}{m_\omega^2}\rho.$$

- The DD model can be seen as an effective model in which the nonlinear behavior of the scalar and vector fields are included in the density dependence of the respective couplings.

Model	T_c (MeV)	ρ_c (fm^{-3})	P_c (MeV/fm^3)	$\frac{\rho_c}{\rho_0}$
⋮				
DD-F	15.24	0.0505	0.245	0.343
TW99	15.17	0.0509	0.241	0.332
DDHδ	15.17	0.0509	0.241	0.332
DD-MEδ	15.32	0.0491	0.235	0.323

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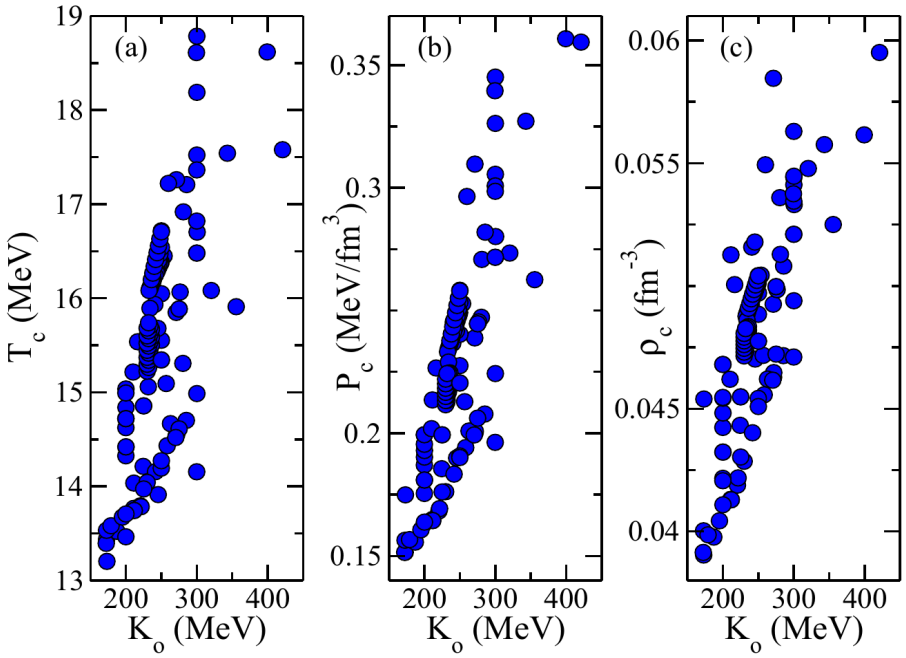
Outline

- Introduction
- Choice of models
- Results
  - Critical parameters and model dependence in the liquid phase
  - Comparison with experimental data
  - Correlations
- Summary

Correlations

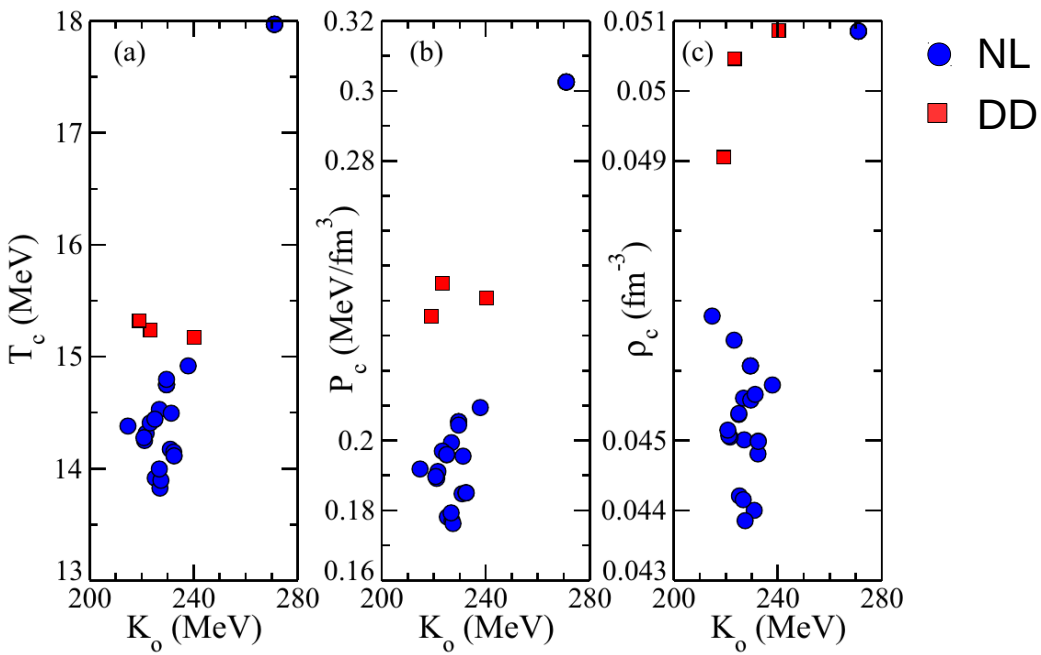
O. Lourenço, B. M. Santos, M. Dutra, and A. Delfino, Phys. Rev. C **94**, 045207 (2016).

- 128 Boguta-Bodmer parametrizations were analyzed and the critical parameters showed an increasing behavior with K_0.



O. Lourenço, M. Dutra, and D. P. Menezes, Phys. Rev. C **95**, 065212 (2017).

- The critical parameters of the CRMF parametrizations as a function of K_0. We also verify an indication of T_c, ρ_c, and P_c as increasing functions of K_0.



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Summary

- The critical parameters T_c , P_c , and ρ_c , which define the limiting point of the phase transition from a gas to a liquid phase have been recalculated with 34 RMF models .

- We have divided these models into six categories and **just two** of them (Z271) and (DD) approaches the experimental critical temperature values.

- By comparing these observations with the neutron star main properties calculated in M. Dutra, O. Lourenço, and D. P. Menezes, Phys. Rev. C 93, 025806 (2016); 94, we see that only density dependent models seem to behave well both at low and high densities, but this statement requires a more consistent analyses and further experimental and observational data.

- We have also verified that the critical parameters present a **correlation** with the **incompressibility**, but the same is not true for other important nuclear matter bulk quantities, such as the energy symmetry and its slope.

Summary and conclusions

Thank you!