XXXVI International Symposium Dynamical Properties of Solids
Cracow, 27-31 August 2017

Properties of localized protons in neutron star matter at finite temperatures for realistic nuclear models

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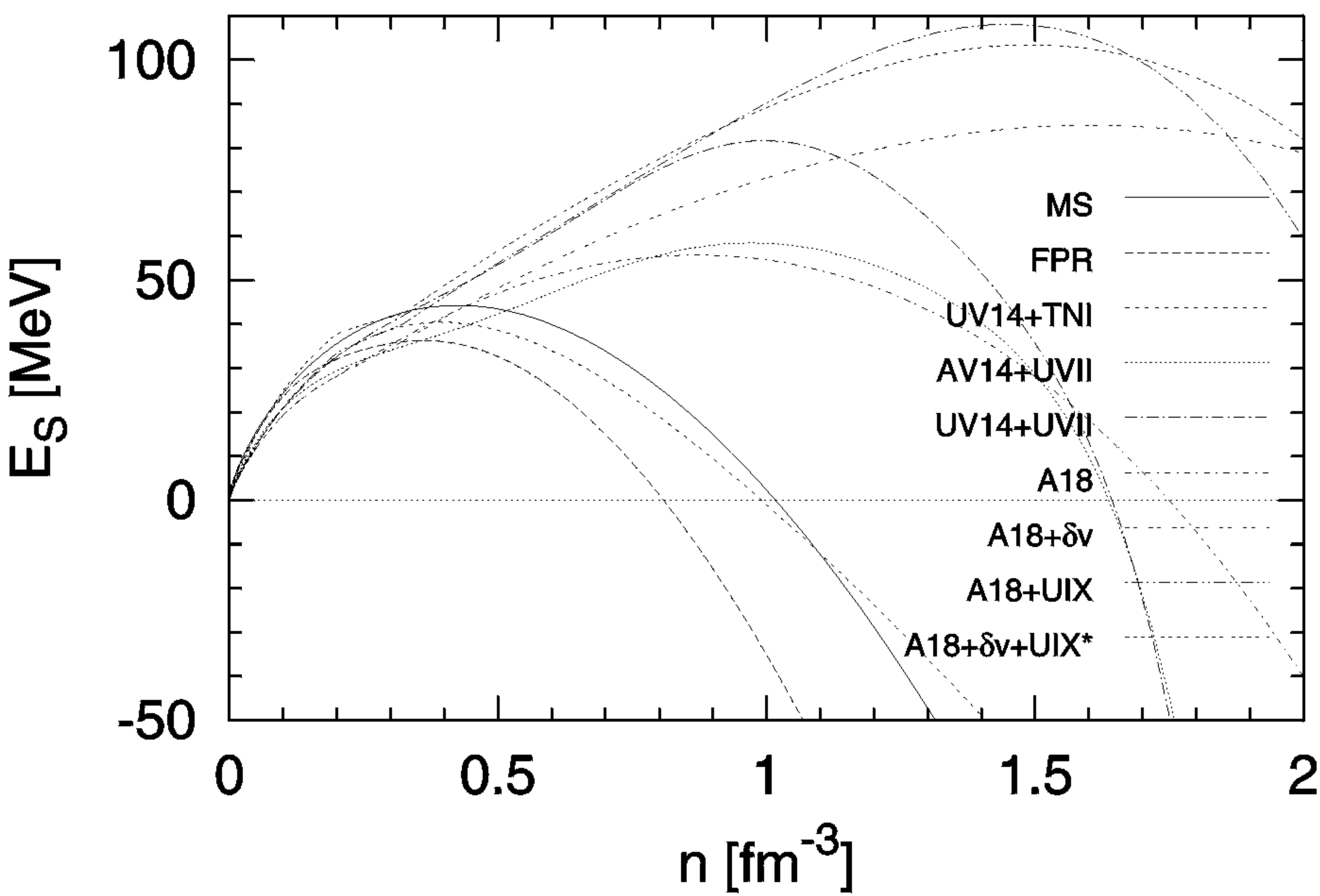
Realistic Nuclear Models:

1. Skyrme (SI’, SII’, SIII’, SL, Ska, SKM, SGII, RATP, T6)
2. Myers-Świątecki (MS)
3. Friedman-Pandharipande-Ravenhall (FPR)
4. UV14+TNI (UV)
5. AV14+UVII (AV)
6. UV14+UVII (UVU)
7. A18
8. A18+δv
9. A18+UIX
10. A18+δv+UIX*

Symmetry Energy of Nuclear Matter

$$E(n,x) = E\left(n,\frac{1}{2}\right) + E_S(n)(2x-1)^2 \qquad x = n_P / n$$

$$E_S(n) = \frac{1}{8}\frac{\partial^2 E(n,x)}{\partial x^2}\bigg|_{x=\frac{1}{2}}$$

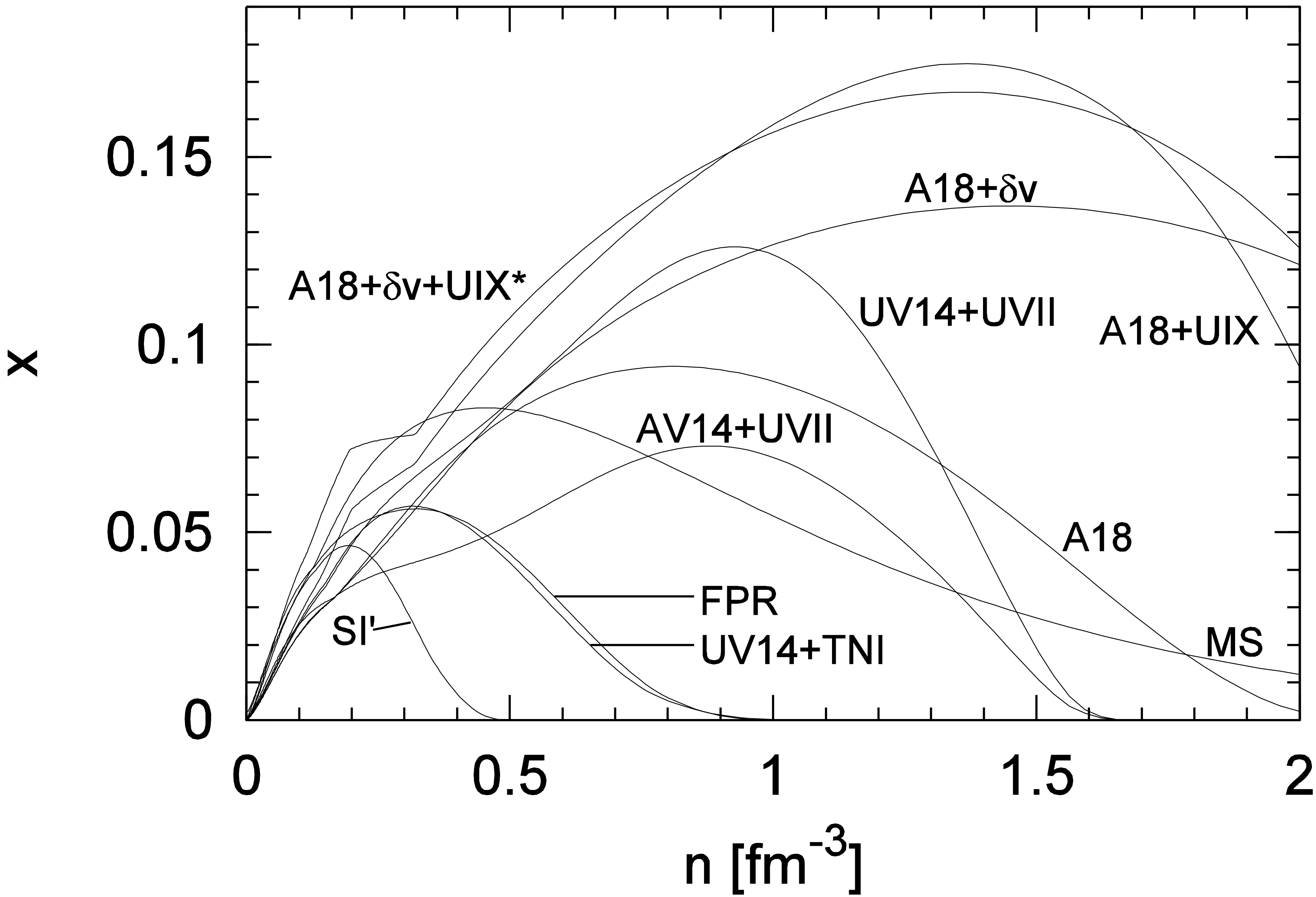


100
50
0
-50
E_S [MeV]
0
0.5
1
1.5
2
n [fm^{-3}]
MS
FPR
UV14+TNI
AV14+UVII
UV14+UVII
A18
A18+δv
A18+UIX
A18+δv+UIX*

Small values of the symmetry energy:

1. Low proton concentration
2. Charge separation instability realized

   e.g. through proton localization

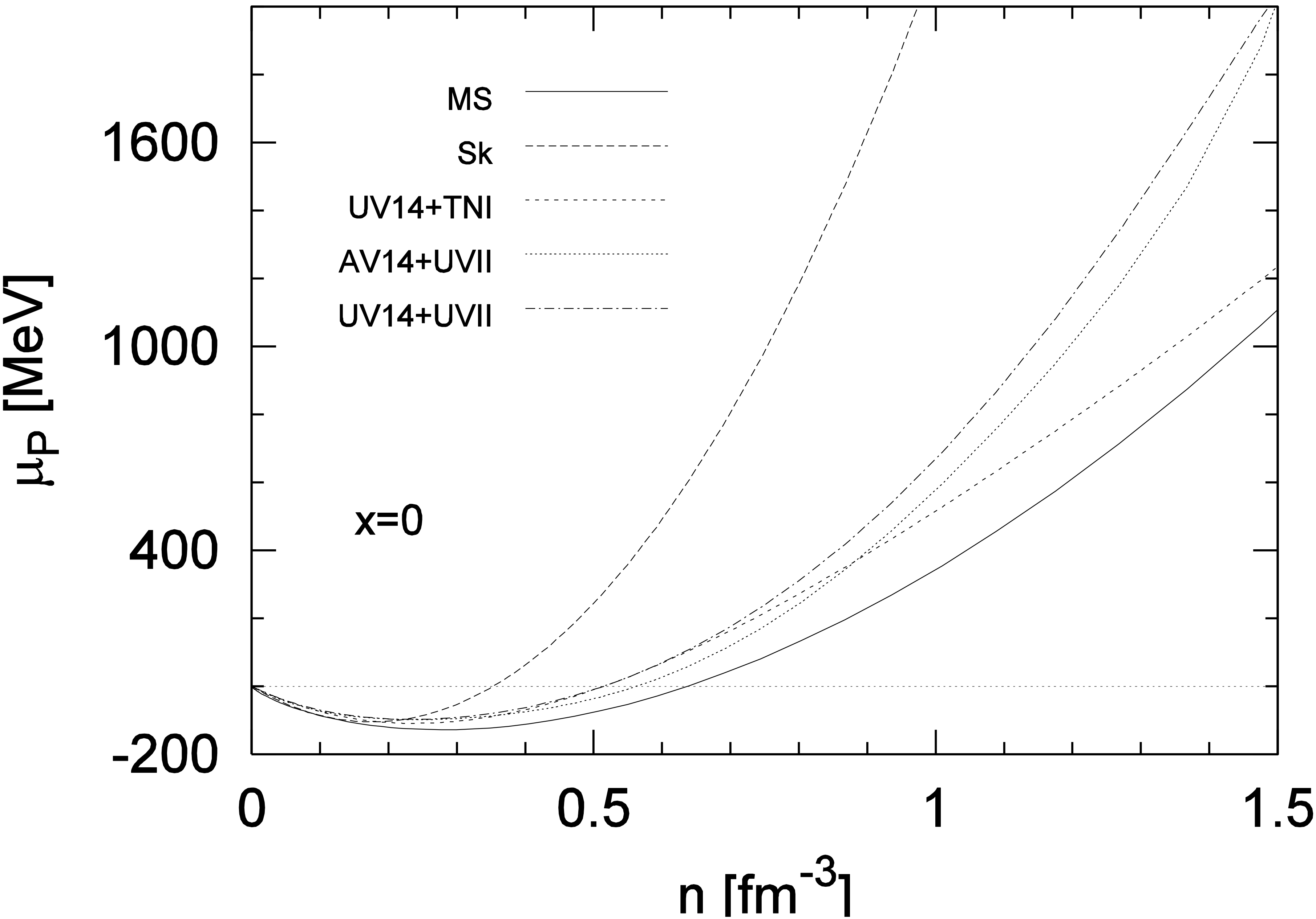


0.15
0.1
0.05
0
x
0
0.5
1
1.5
2
n [fm^{-3}]
A18+δv+UIX*
A18+δv
UV14+UVII
A18+UIX
AV14+UVII
A18
FPR
UV14+TNI
SI'
MS

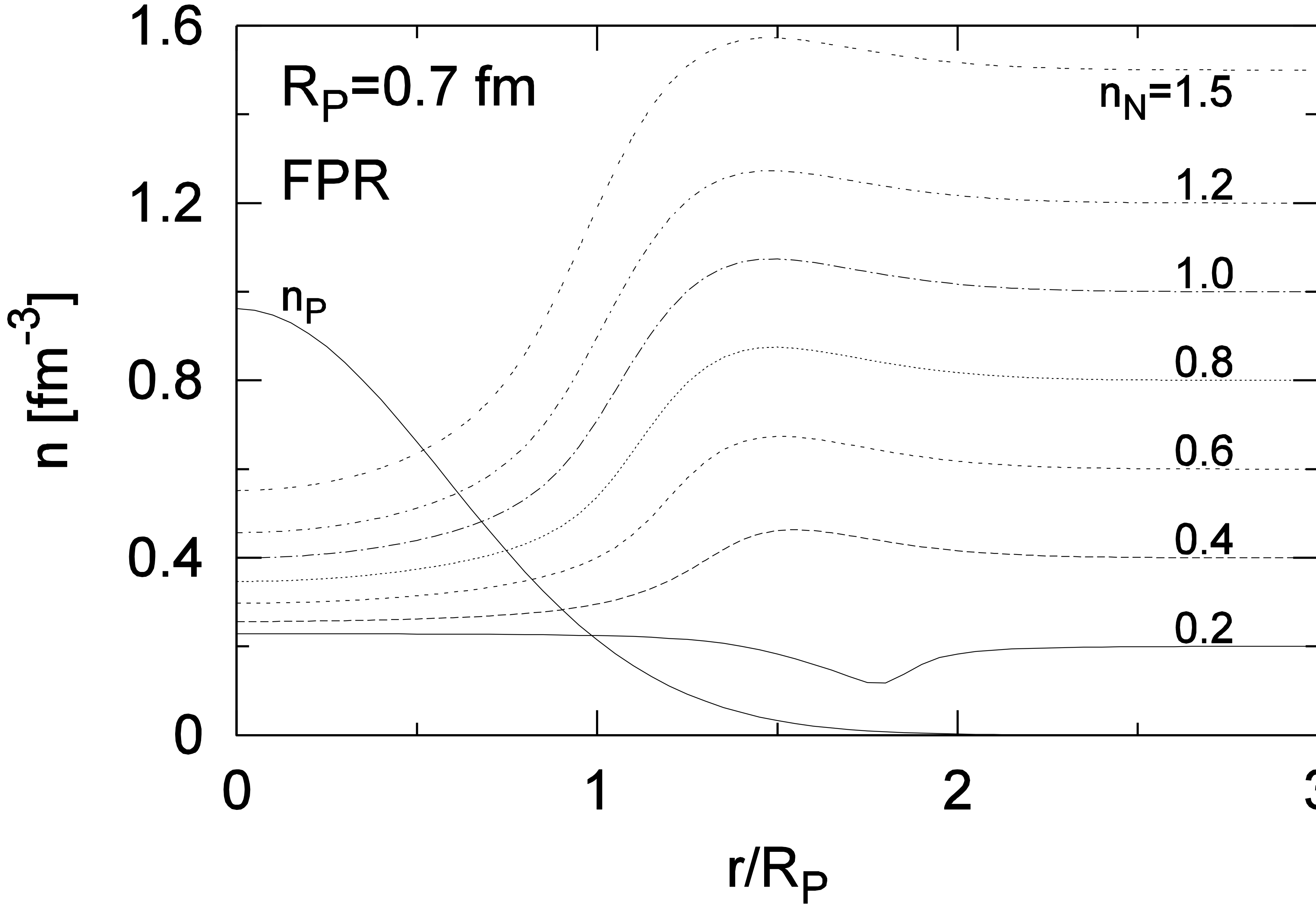
Model of Proton Impurities in Neutron Star Matter (M. Kutschera, W. Wójcik)

We divide the system into spherical Wigner-Seitz cells, each of them enclosing a single proton.

The volume of the cell: $V = \dfrac{1}{n_P}$



MS
Sk
UV14+TNI
AV14+UVII
UV14+UVII
x=0
1600
1000
400
-200
0
0.5
1
1.5
μ_P [MeV]
n [fm^{-3}]



1.6
1.2
0.8
0.4
0
n [fm^-3]
R_P=0.7 fm
FPR
n_N=1.5
1.2
1.0
0.8
0.6
0.4
0.2
n_P
0
1
2
3
r/R_P

The energy of the cell of uniform phase: $E_0 = V\varepsilon(n_N, n_P)$

$$\varepsilon(n_N, n_P) \approx \varepsilon(n_N) + \mu_P(n_N) n_P \qquad E_0 = \mu_P(n_N) + V\varepsilon(n_N)$$

The energy of the cell with localized proton:

$$E_L = \int_V \left\{ \Psi_P^*(r) \left[-\frac{\nabla^2}{2m_P} + \mu_P(n(r)) \right] \Psi_P(r) + \varepsilon(n(r)) + B_N \left(\vec{\nabla} n(r) \right)^2 \right\} d^3 r$$

$$\Psi_P(r) = \left(\frac{2}{3} \pi R_P^2 \right)^{-\frac{3}{4}} \exp\left(-\frac{3}{4} \frac{r^2}{R_P^2} \right)$$

Potential	$n_{loc}\left[fm^{-3}\right]$	$R_P^{loc}\left[fm\right]$
MS	1.033	0.906
SI’	0.351	1.570
SII’	0.361	1.688
SIII’	0.337	1.552
SL	0.964	1.384
Ska	1.016	0.804
SKM	0.979	1.330
FPR	0.721	1.262
UV14+TNI	0.731	1.209
AV14+UVII	0.789	0.971
UV14+UVII	0.766	0.913
A18	1.493	1.136
A18+δv	1.627	0.915
A18+UIX	0.645	0.911
A18+δv+UIX*	0.819	0.878

Properties of nuclear matter at T>0

The free energy per baryon:

$$F = E - T\left(\left(1 - x\right)S_N + xS_P\right)$$

where the entropy per baryon

$$S_{N,P} = \frac{5}{3}\frac{1}{n_{N,P}}\frac{1}{\left(2\pi\right)^2}\left(2m^*_{N,P}T\right)^{3/2}J_{3/2}\left(\eta_{N,P}\right) - \frac{1}{2}\eta_{N,P}$$

The unknown quantity $\eta_{N,P}$ comes from:

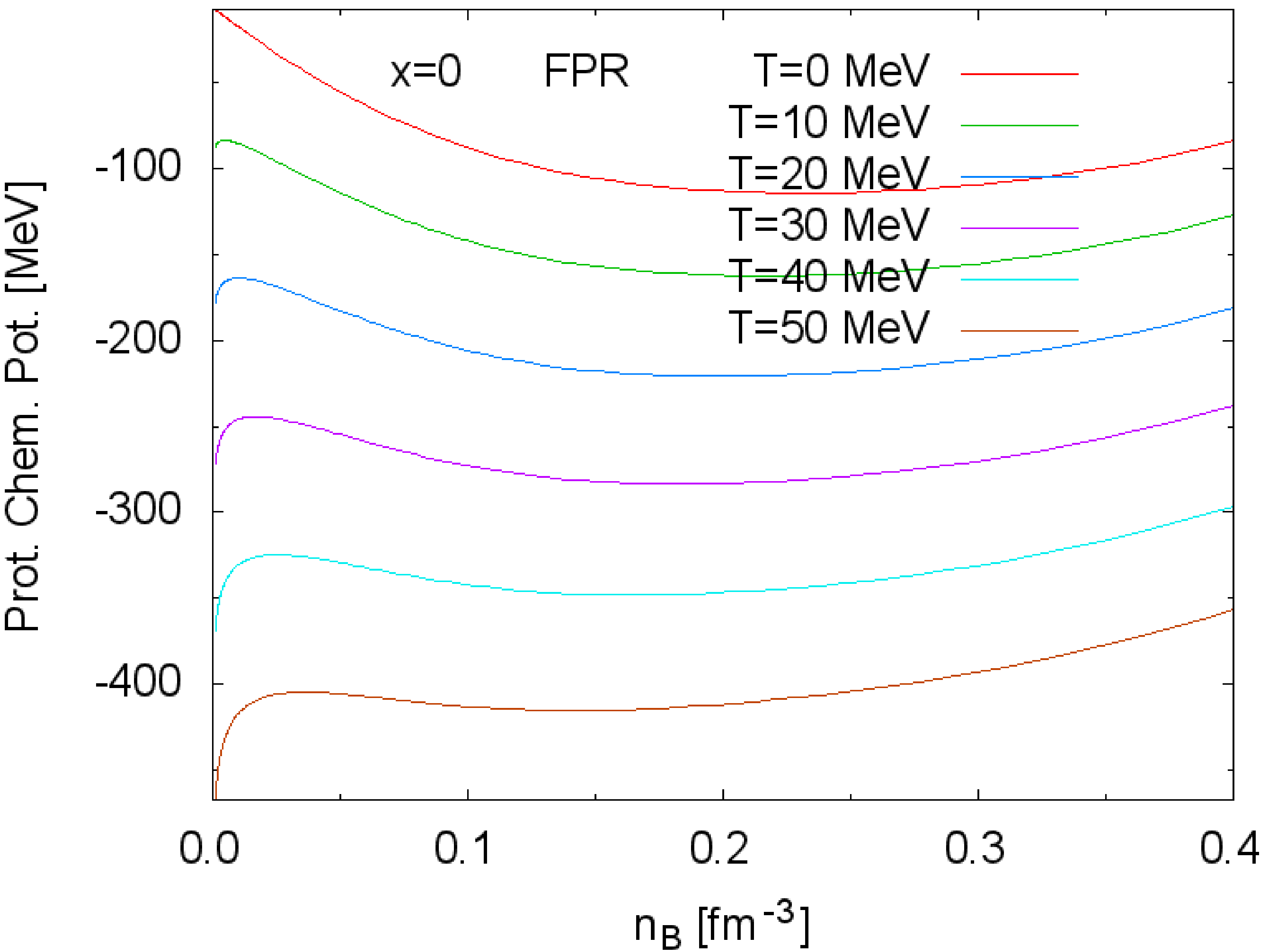
$$n_{N,P} = \frac{2}{\left(2\pi\right)^2}\left(2m^*_{N,P}\right)^{3/2}J_{1/2}\left(\eta_{N,P}\right)$$

Fermi integrals are defined as:

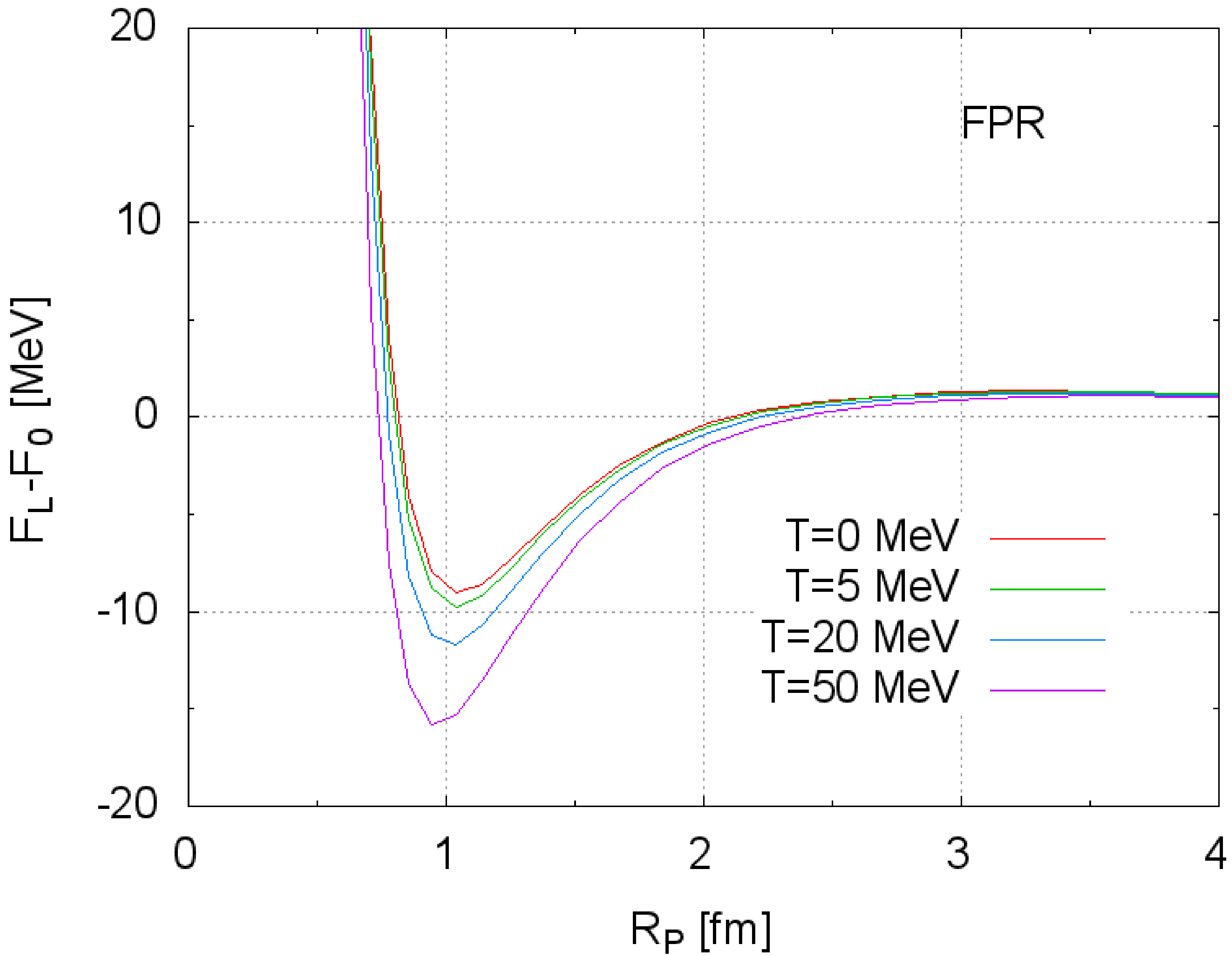
$$J_\nu(\eta) = \int_0^\infty dx \frac{x^\nu}{1+e^{x-\eta}}$$

Nucleon chemical potentials are the derivatives of the free energy density

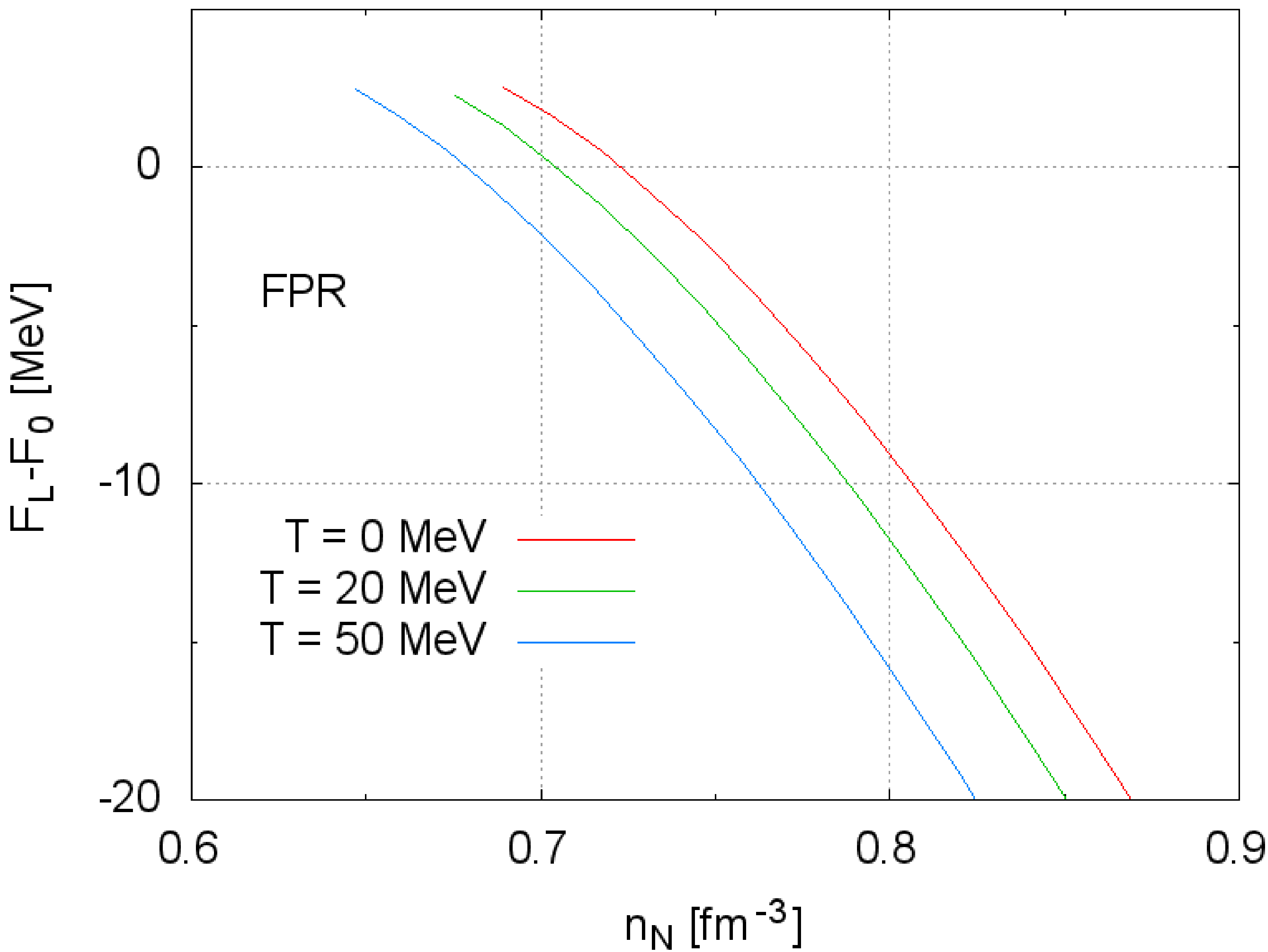
$$\mu_{N,P} = \frac{\partial f}{\partial n_{N,P}}$$



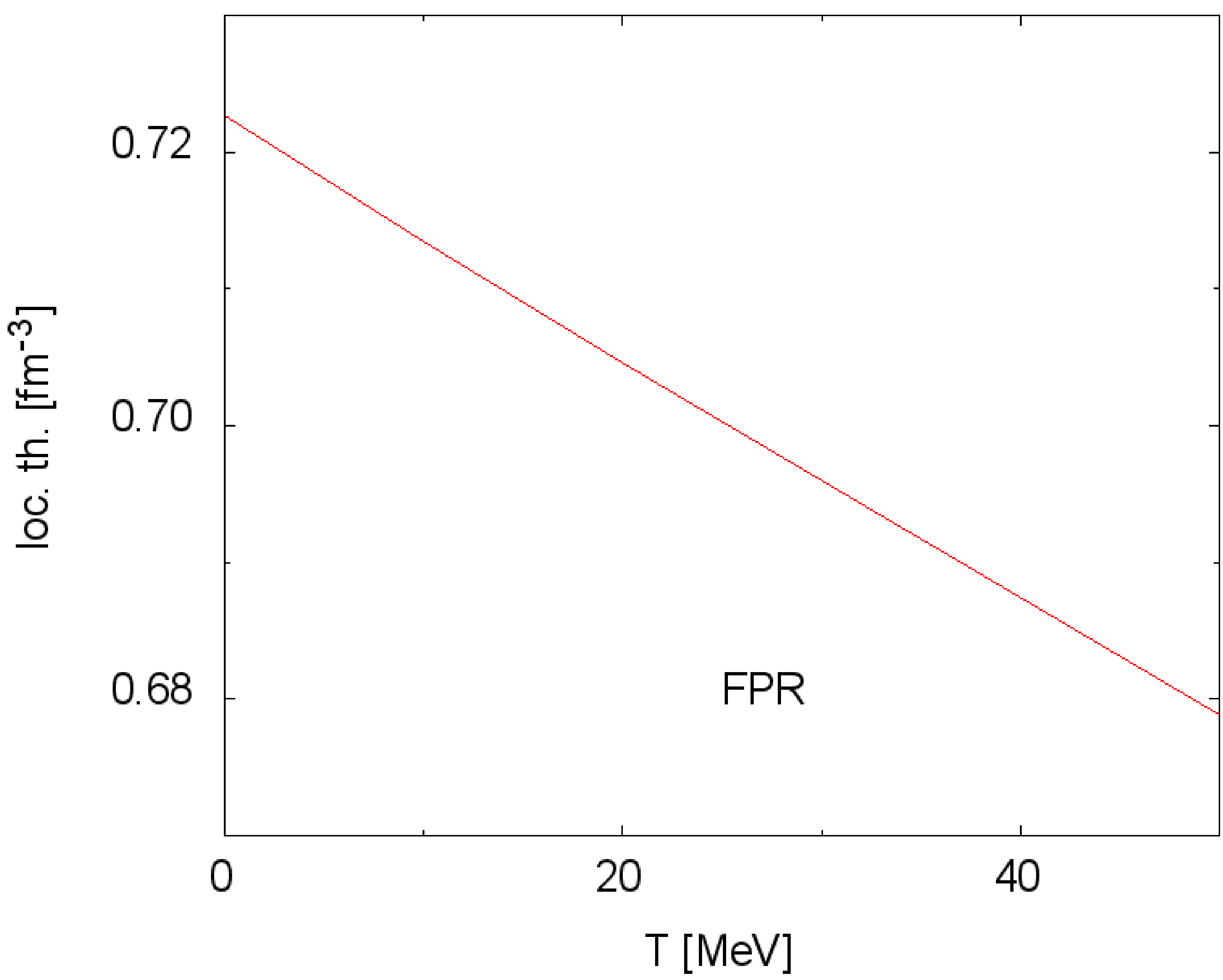
x=0
FPR
T=0 MeV
T=10 MeV
T=20 MeV
T=30 MeV
T=40 MeV
T=50 MeV
-100
-200
-300
-400
Prot. Chem. Pot. [MeV]
0.0
0.1
0.2
0.3
0.4
n_B [fm^-3]



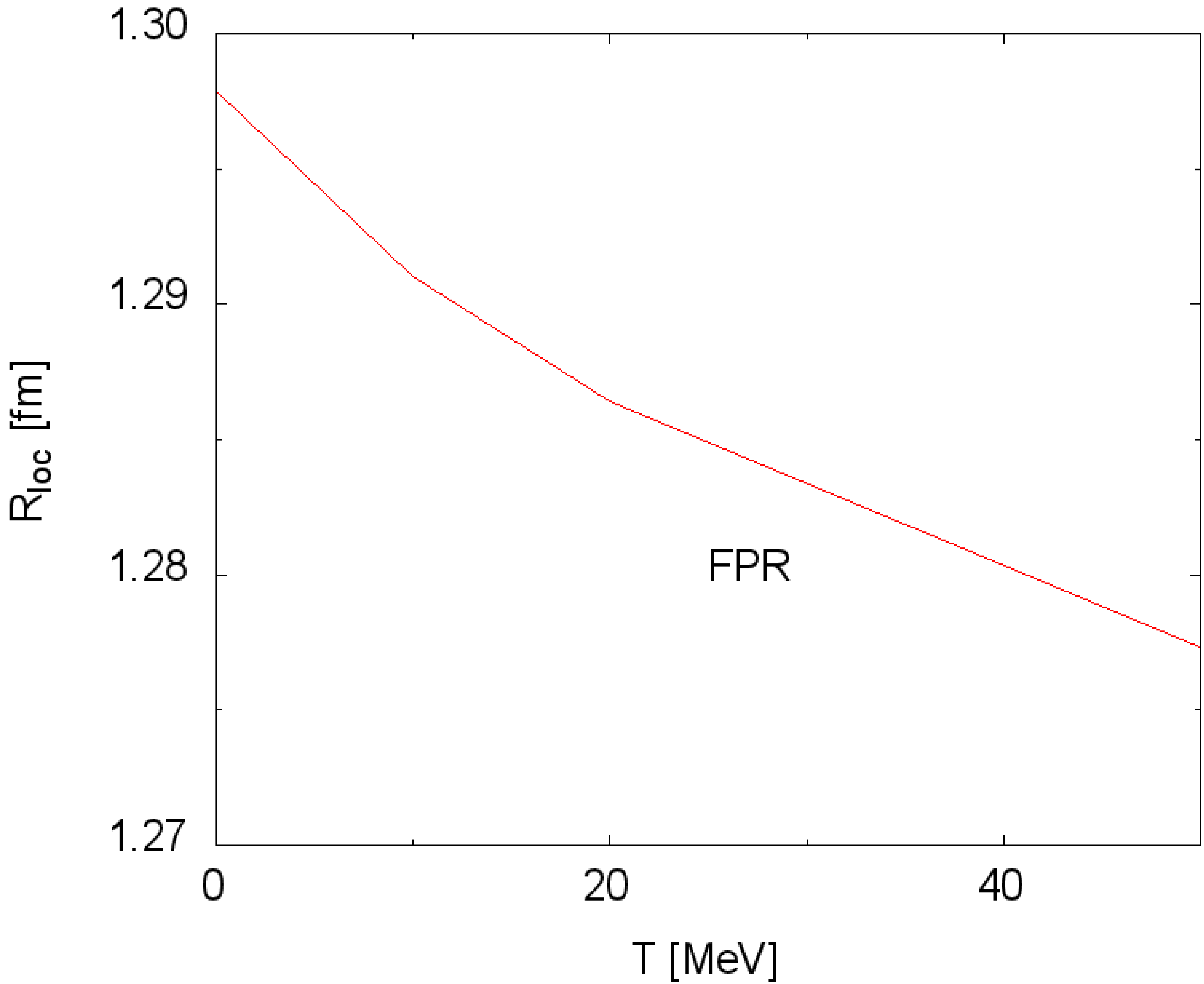
FPR
T=0 MeV
T=5 MeV
T=20 MeV
T=50 MeV
$F_L - F_0$ [MeV]
R_P [fm]
20
10
0
-10
-20
0
1
2
3
4



FPR
T = 0 MeV
T = 20 MeV
T = 50 MeV
$F_L - F_0$ [MeV]
n_N [fm^{-3}]
0
-10
-20
0.6
0.7
0.8
0.9



loc. th. [fm^-3]
0.72
0.70
0.68
FPR
0
20
40
T [MeV]


1.30
1.29
1.28
1.27
R_{loc} [fm]
FPR
0
20
40
T [MeV]

Conclusions

1. Symmetry energy implies the inhomogeneity of dense nuclear matter in neutron stars.
2. Localization of protons as an universal state of dense nuclear matter in neutron stars.
3. Nonzero temperature lowers the localization threshold density and diminishing the size of the proton wave function.
4. Localization is still present at very high temperature.

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