Hot and dense matter beyond relativistic mean field theory

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X.Z. and Madappa Prakash (Ohio U.), PRC.93.055805 (2016) [arXiv: 1602.07665]

INT Program: INT-16-2b "The Phases of Dense Matter", summer, 2016

Outline

- Motivations
- Mean field theory (MFT) and two-loop (TL) calculations in the framework of quantum hadro-dynamics (QHD): zero temperature
- Finite temperature calculations
- Summary

Motivations

- Dense matter equation of state (EOS) is needed in astrophysics simulations
- QHD's MFT approximation is widely used to model the EOS, but TL terms have not been well studied
- Goal is to compare MFT and MFT+TL on EOS and nucleon optical potential (relevant for medium energy heavy ion collisions)

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(p,n) fields

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Pseudovector coupling due to Chiral symmetry

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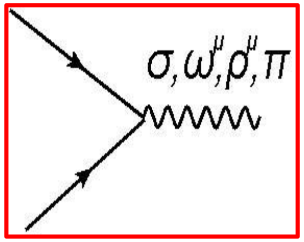

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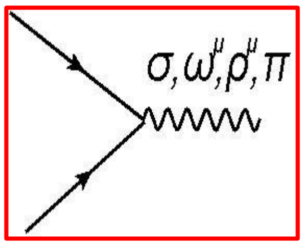

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$$\mathcal{L}_{\text{meson}} = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \left(\frac{1}{2} + \frac{\kappa_3}{3!}\frac{g_s\phi}{M} + \frac{\kappa_4}{4!}\frac{g_s^2\phi^2}{M^2}\right)m_s^2\phi^2 + \frac{1}{2}\partial^\mu\pi^i\partial_\mu\pi_i - \frac{1}{2}m_\pi^2\pi^i\pi_i$$
$$-\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m_v^2 V_\mu V^\mu - \frac{1}{4}\rho^i_{\mu\nu}\rho_i^{\mu\nu} + \frac{1}{2}m_\rho^2\rho^i_\mu\rho_i^\mu\,,$$

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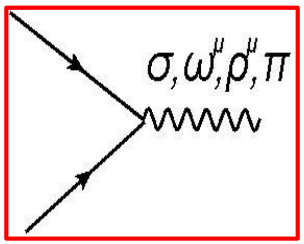

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Masses are given as known, 5 couplings need to be fixed

g_s^2	g_v^2	g_ρ^2	κ_3	κ_4

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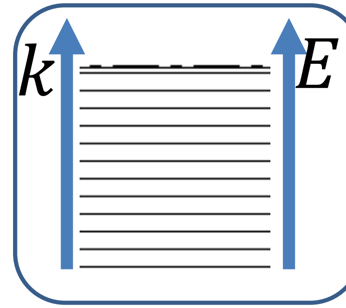

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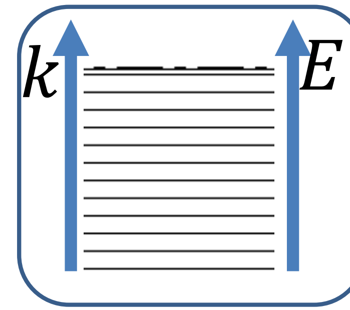

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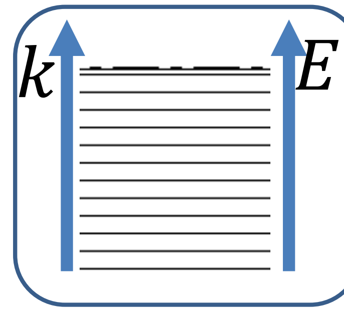

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$$\rho_{s,p}+\rho_{s,n}\equiv\gamma_s\sum_i\int\frac{d^3\boldsymbol{k}}{(2\pi)^3}\frac{M^*}{E^*(k)}n_i(k)=-\frac{\partial\mathcal{V}(\overline{\phi})}{\partial M^*}$$

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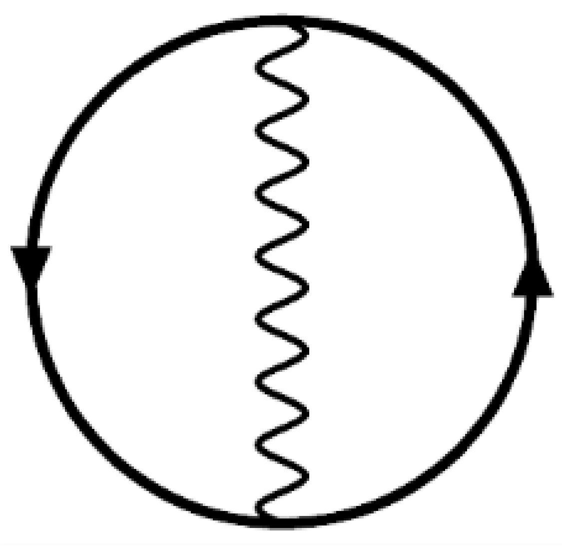

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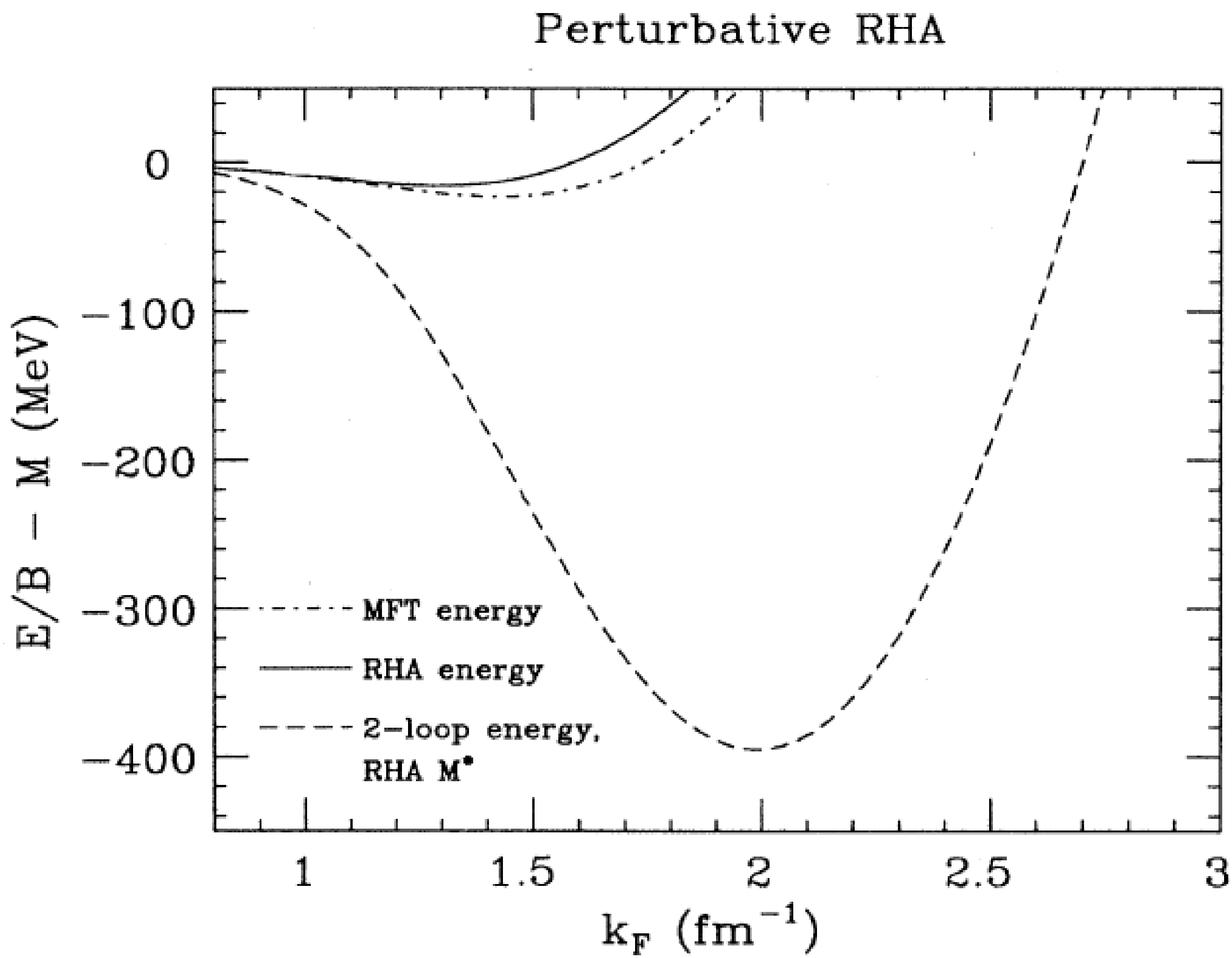

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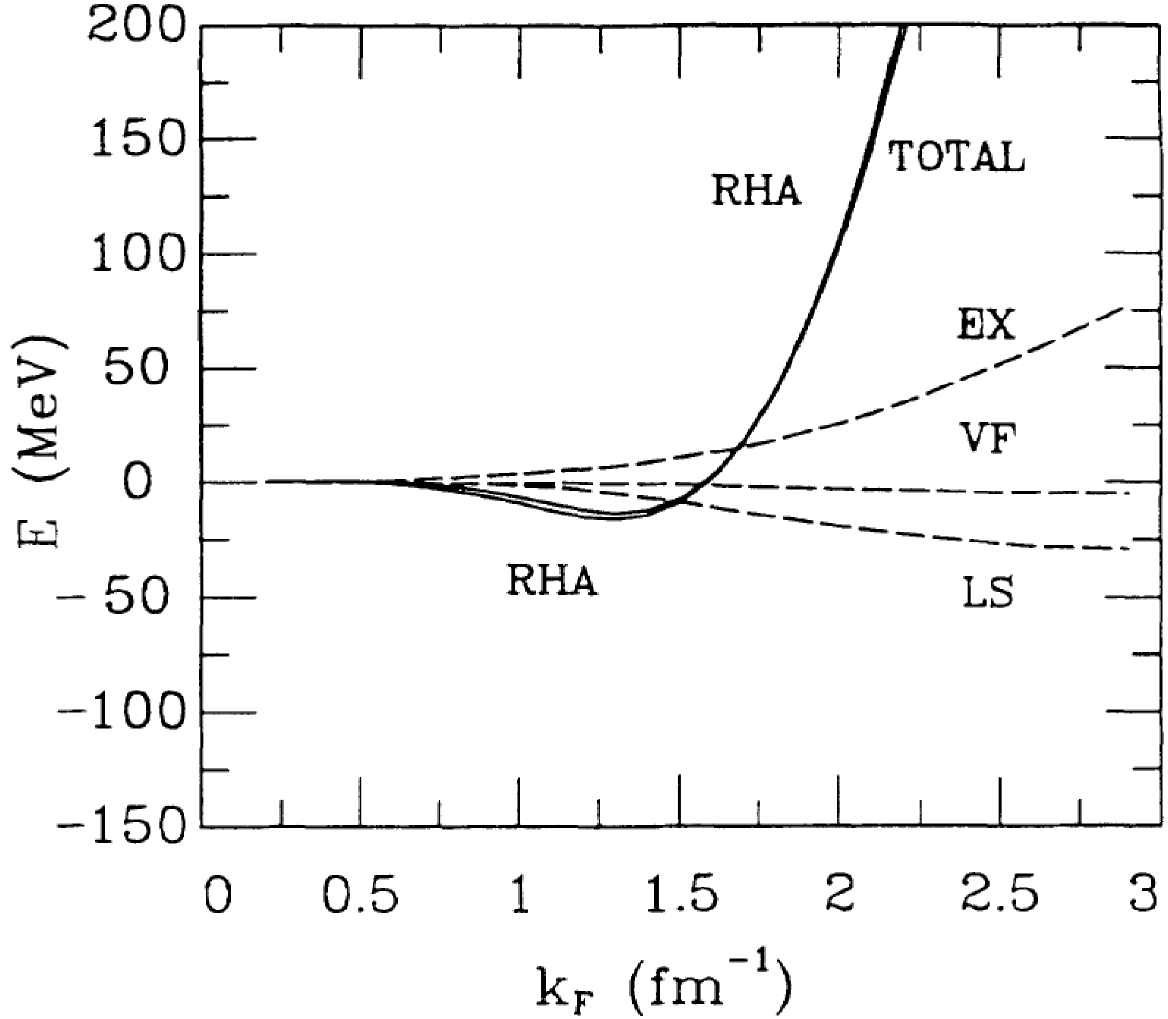

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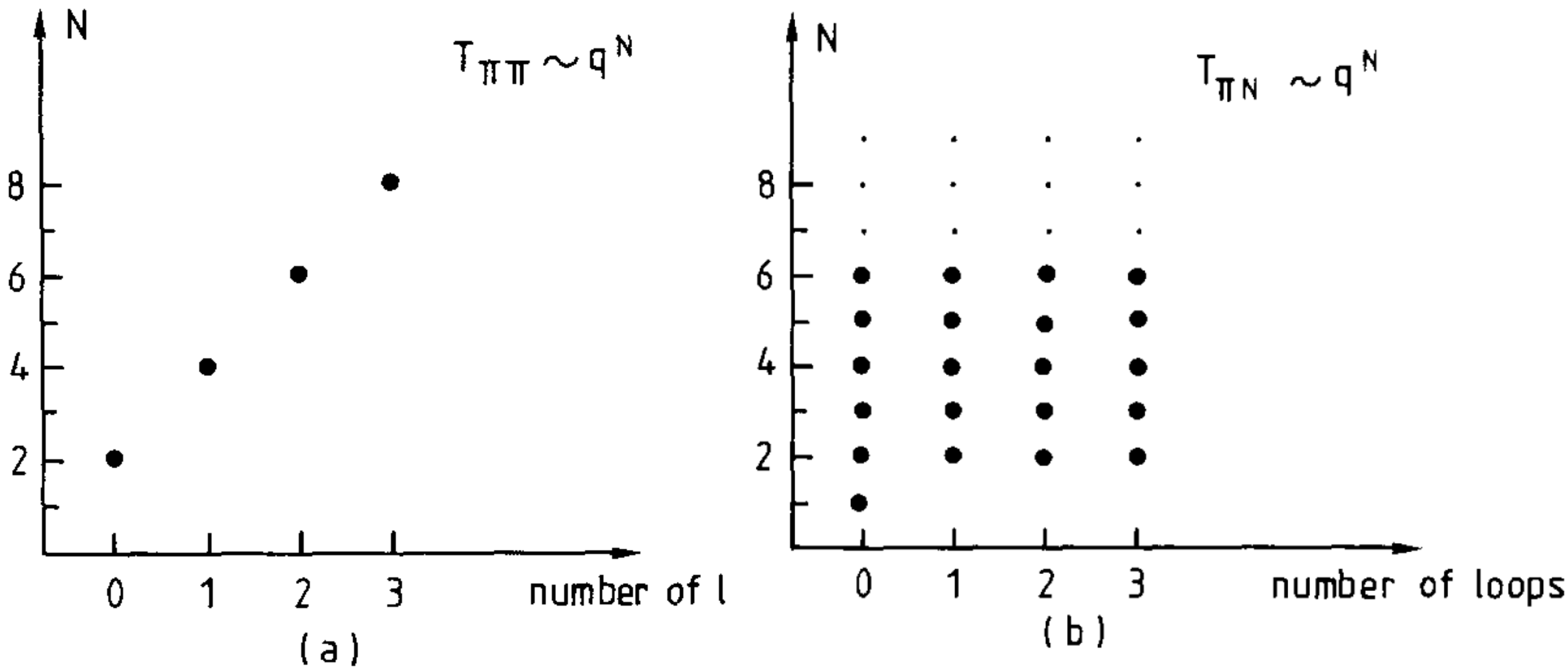

- R. J. Furnstahl, R. J. Perry, and B. D. Serot, Phys. Rev. C **40**, 321 (1989)
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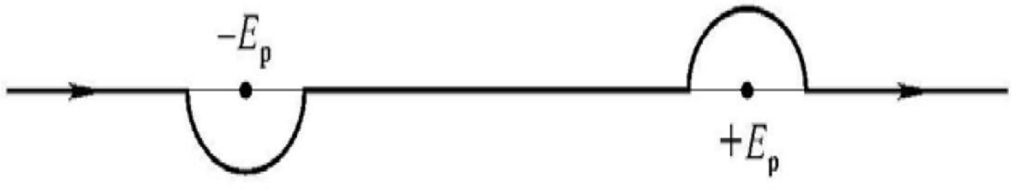

- R. J. Furnstahl, R. J. Perry, and B. D. Serot, Phys. Rev. C **40**, 321 (1989)
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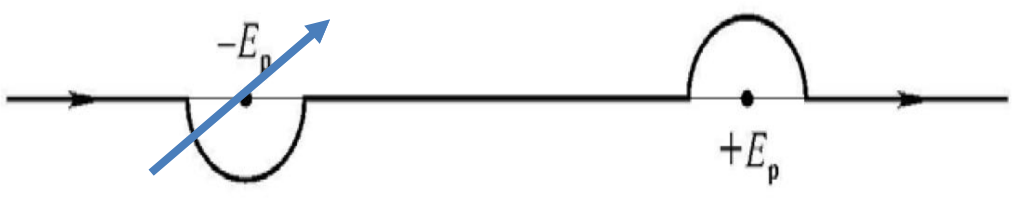

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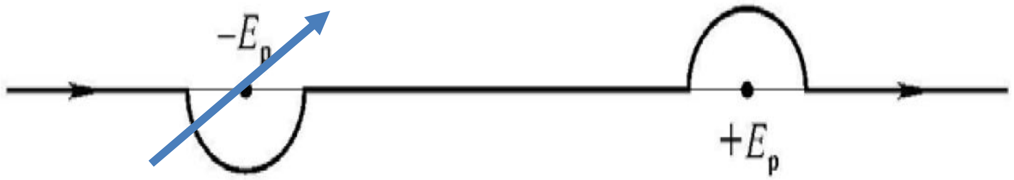
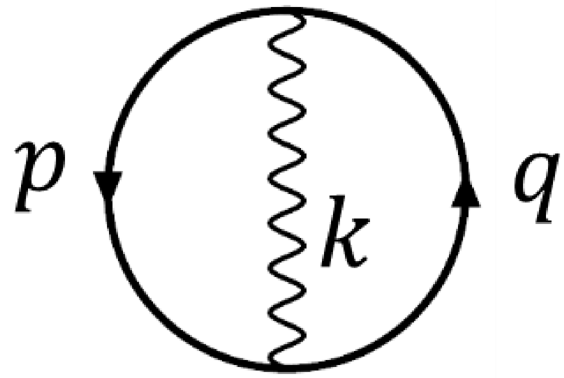
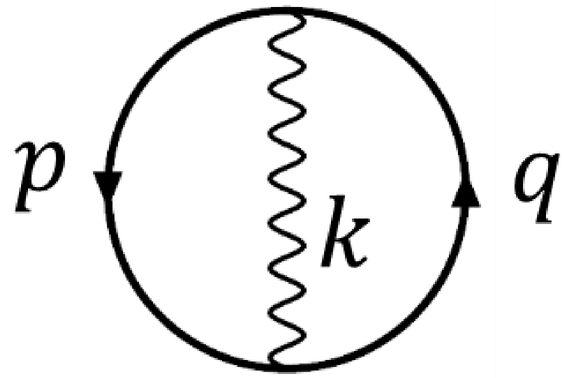
- Many body: Y. Hu, J.McIntire, and B. Serot, Nucl. Phys. A**794**, 187 (2007).



TL contributions



TL contributions



$$\frac{\gamma_s}{4} g^2 \int \frac{d^4p}{(2\pi)^4} \frac{d^4q}{(2\pi)^4} \, \mathrm{Tr}\left[G(q)\Gamma(p-q)G(p)\Gamma(q-p)\right] D(q-p)$$

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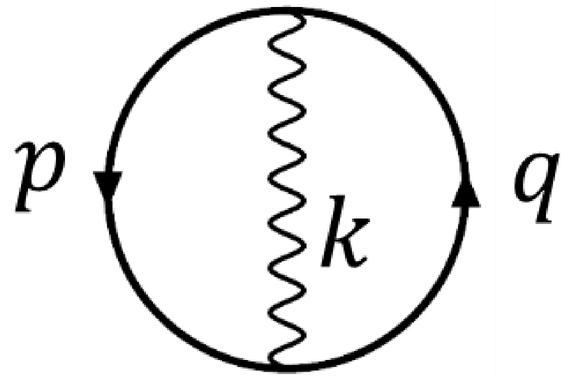

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Y. Hu, J.McIntire, and
B. Serot, Nucl. Phys.A
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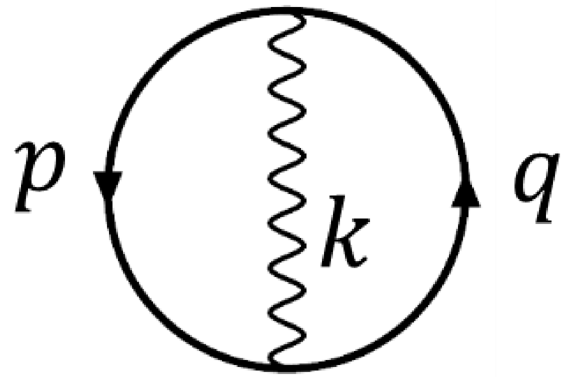
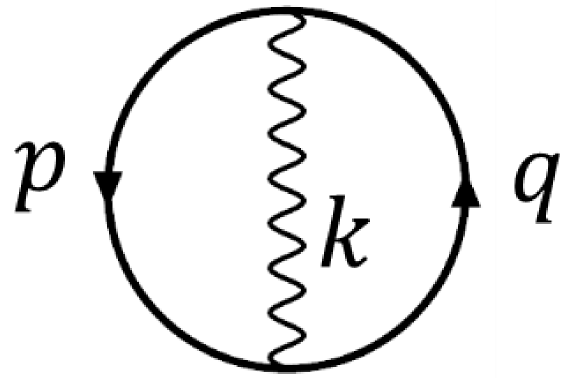


$$\frac{\gamma_s}{4} g^2 \int \frac{d^4p}{(2\pi)^4} \frac{d^4q}{(2\pi)^4} \mathrm{Tr}\left[G(q)\Gamma(p-q)G(p)\Gamma(q-p)\right] D(q-p)$$

Y. Hu, J.McIntire, and B. Serot, Nucl. Phys.A **794**, 187 (2007)

$$\delta\mathcal{E}_{(1,\phi,\mathrm{Vacuum\,Fluctuation})} = \sum_{m=1}^{\infty} a_m (g_s\overline{\phi})^m$$

TL contributions



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Y. Hu, J.McIntire, and B. Serot, Nucl. Phys.A **794**, 187 (2007)

$$\delta\mathcal{E}_{(1,\phi,\mathrm{Vacuum\,Fluctuation})} = \sum_{m=1}^{\infty} a_m (g_s\overline{\phi})^m$$

Absorbed into contact terms in lagrangian

TL contributions

$$\delta\mathcal{E}_{(1,\phi)} = -\frac{\gamma_s}{4} g_s^2 \int d\tau_{\boldsymbol{p}} d\tau_{\boldsymbol{q}}\ f_s(p^*, q^*) D(k; m_s^*) \left[n_p(p) n_p(q) + n_n(p) n_n(q) \right]$$

$$d\tau_{\boldsymbol{p}} \equiv d^3\boldsymbol{p} / \left[(2\pi)^3 2E^*(p) \right], \quad f_s(p^*, q^*) \equiv 4\left(p^* \cdot q^* + M^{*2} \right), \quad D(k; m) \equiv \frac{1}{k \cdot k - m^2}$$

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Impact EOS, and $\epsilon_{(1),i}(p) = \epsilon_{(0),i}(p) + \delta\epsilon_{(1),i}(p)$

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Impact EOS, and $\epsilon_{(1),i}(p) = \epsilon_{(0),i}(p) + \delta\epsilon_{(1),i}(p)$

Note: TLs also modifies bg's dependence on density

Couplings

	g_s^2	g_v^2	g_ρ^2	κ_3	κ_4	L (MeV)
MFT	96.36	118.45	70.13	2.08	−6.77	103.62
TL(235)	71.26	49.58	60.72	5.94	−2.48	83.66
TL(250)	74.03	56.58	57.97	4.84	−4.47	85.09
TL(270)	74.65	61.45	58.06	3.70	1.97	84.51

TL calculations with different incompressibilities, 235, 250, 270 MeV

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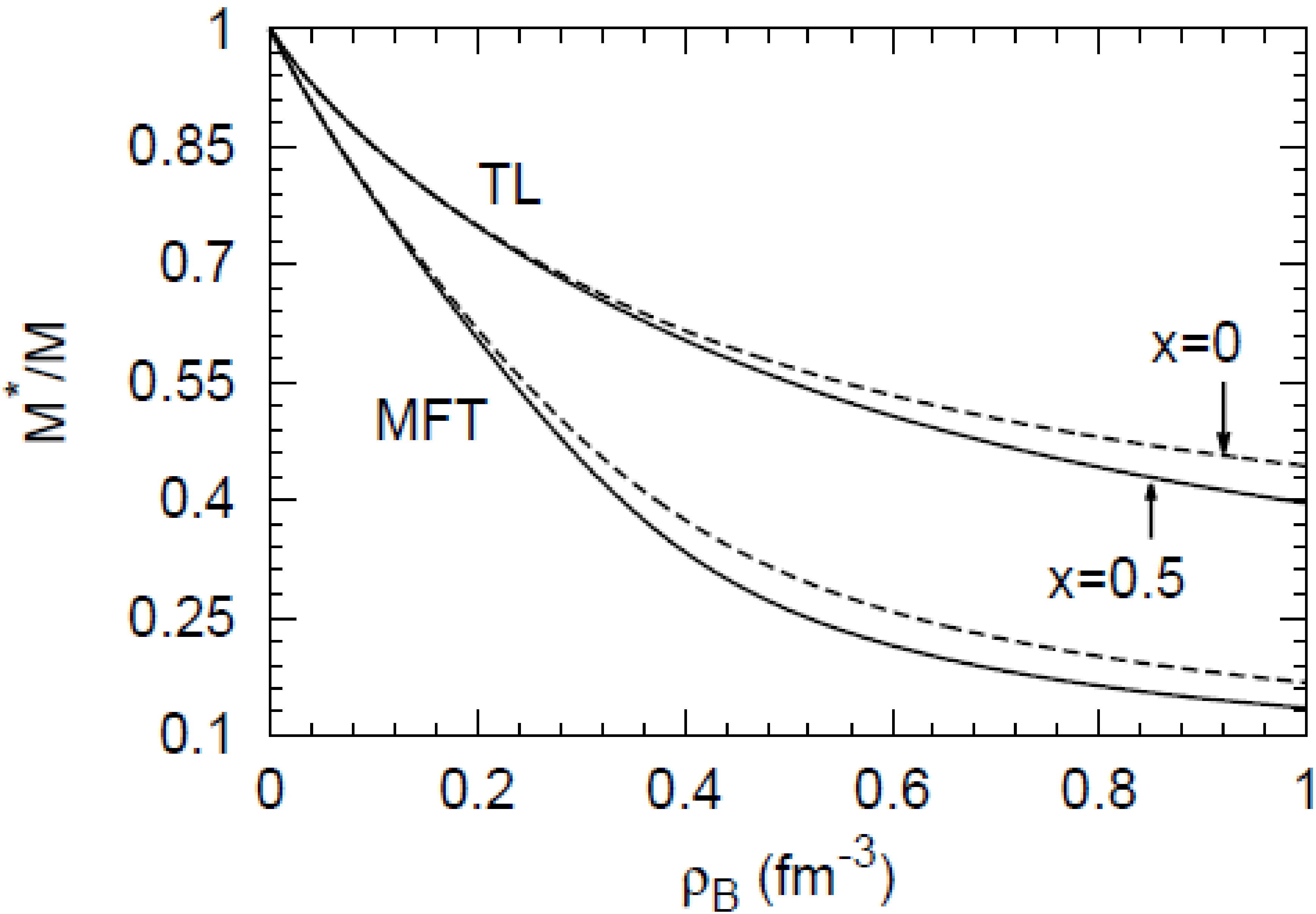
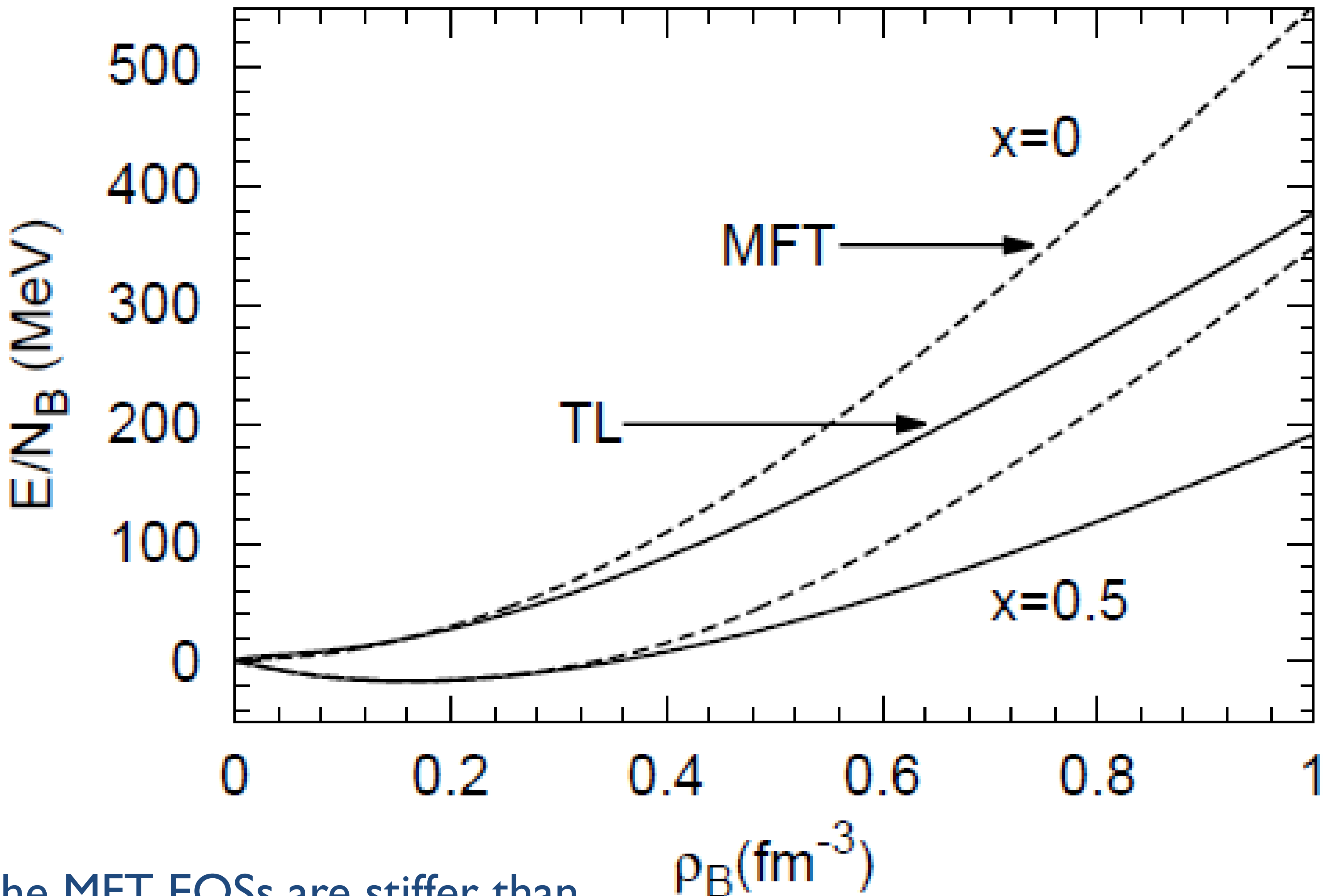
TL calculations with different incompressibilities, 235, 250, 270 MeV

- In the MFT, the scalar coupling is smaller than the vector coupling, while in the TL calculation the former is larger
- The TL calculation's L is smaller than the MFT's

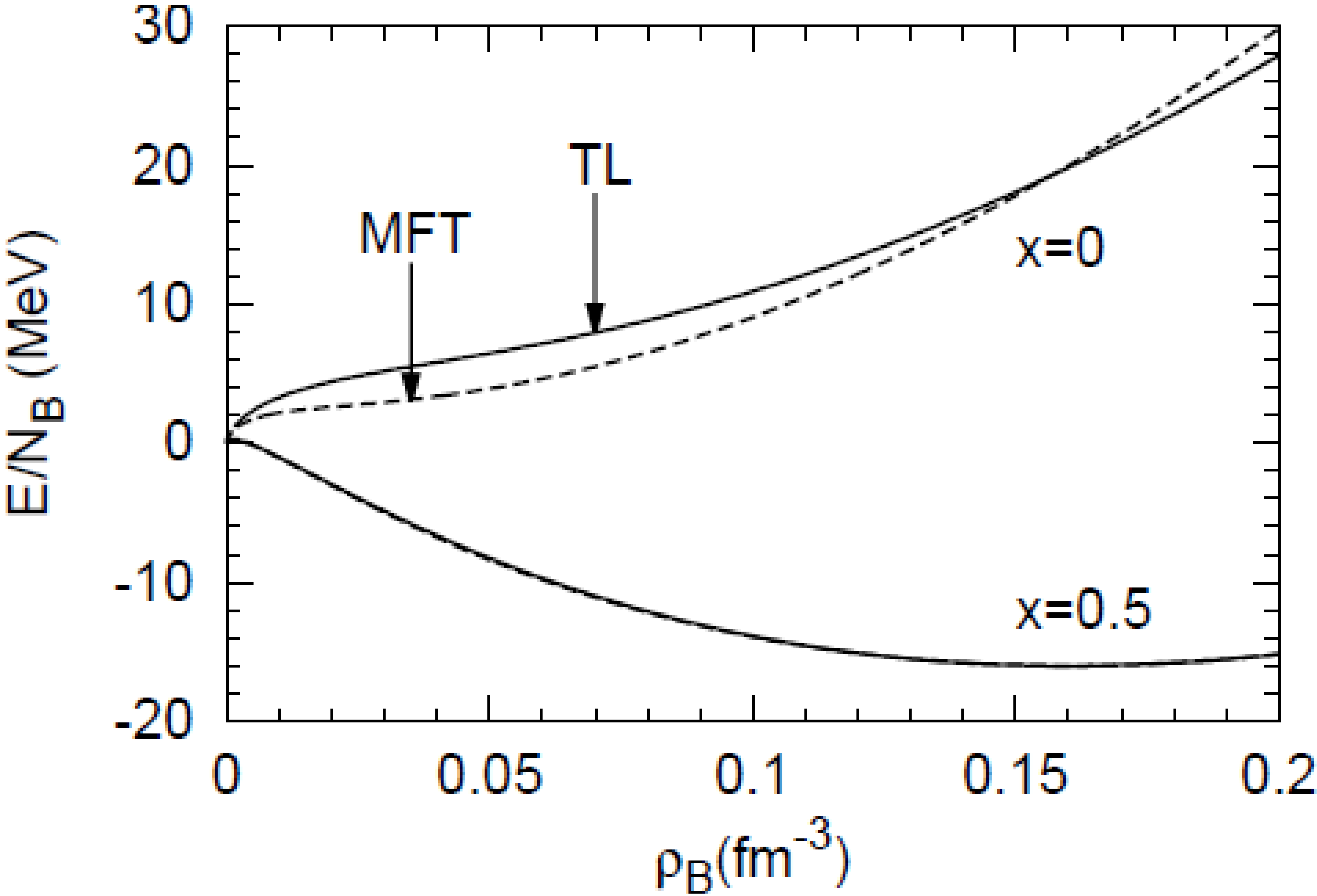
Zero T results



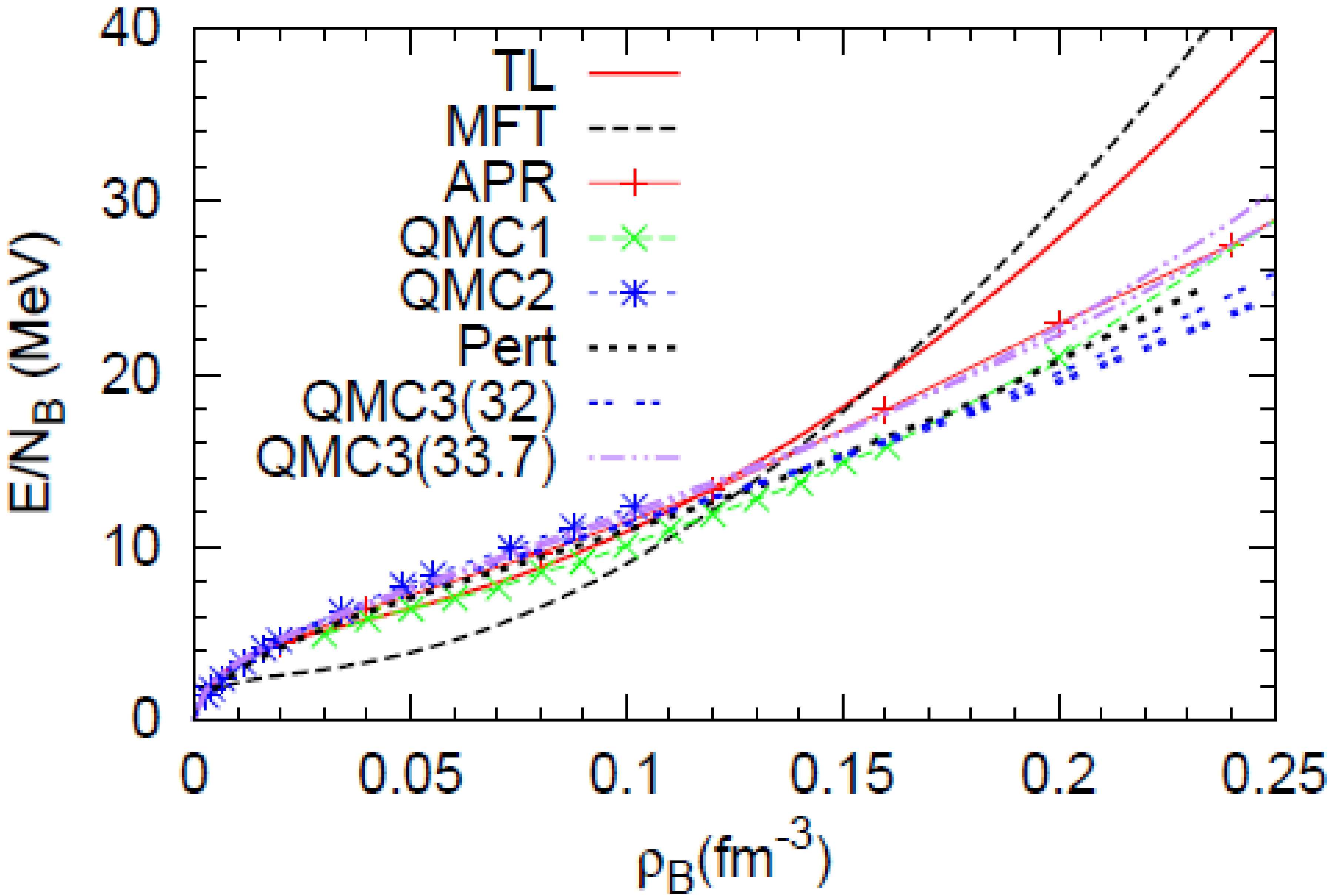
The TL calculation is more nonrelativistic than the MFT, for both pure neutron matter (PNM) and symmetrical nuclear matter (SNM)



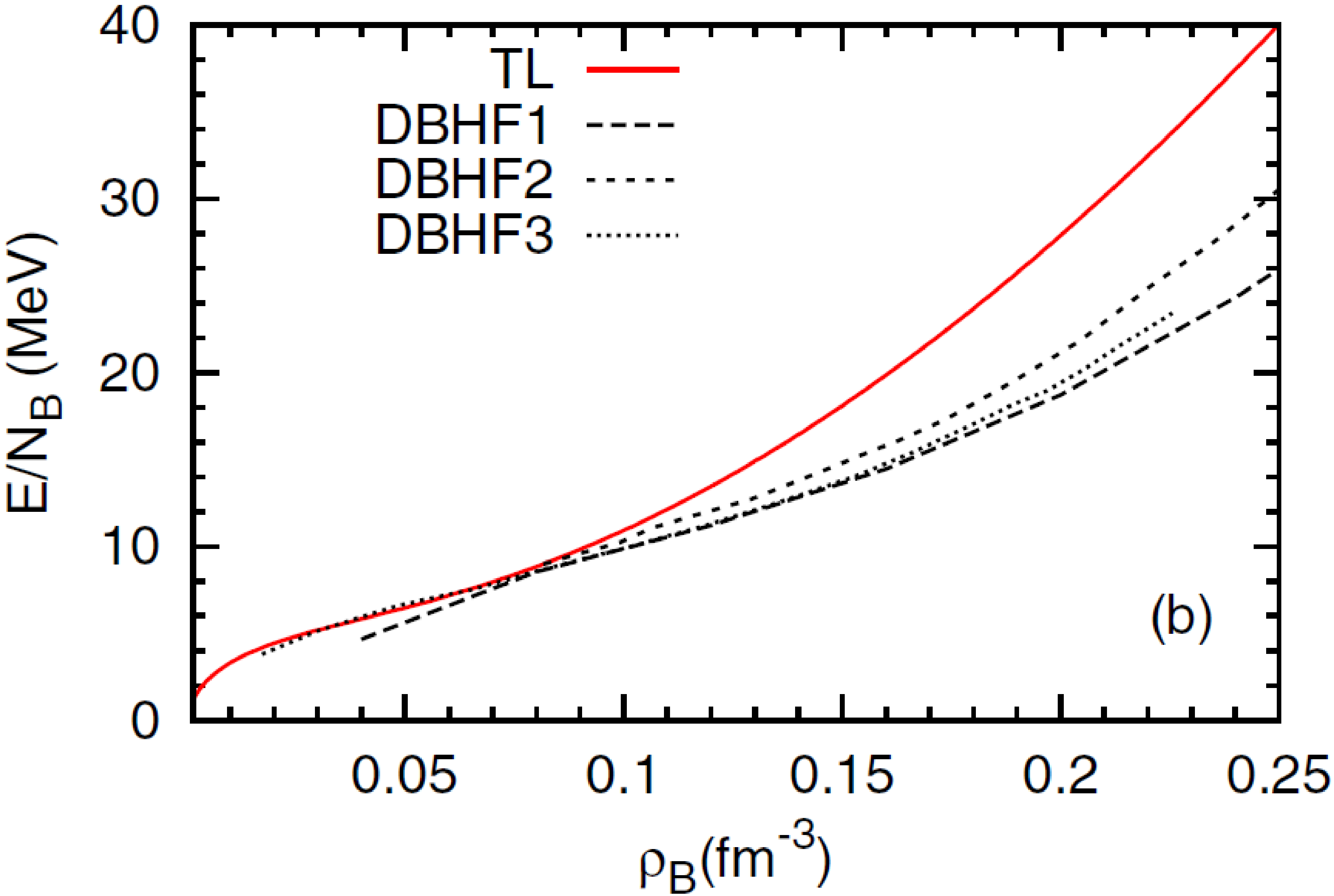
The MFT EOSs are stiffer than the TLs beyond saturation density



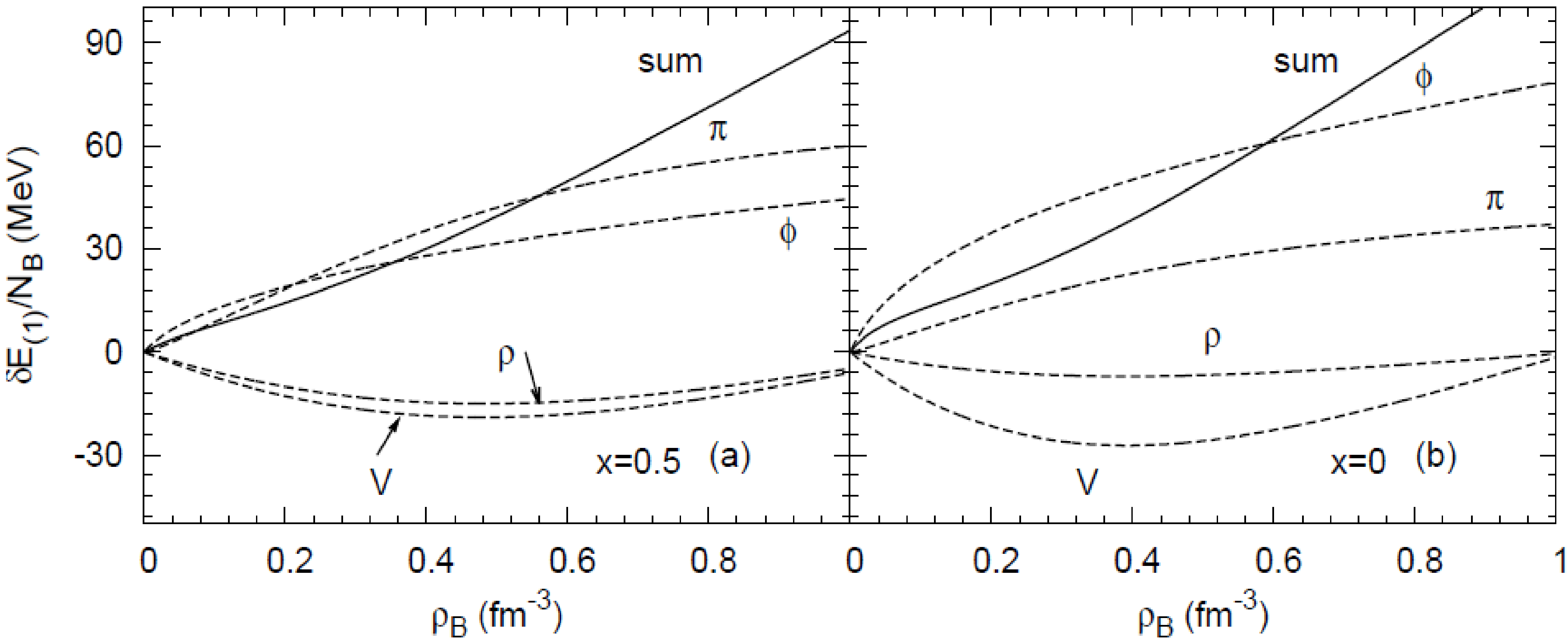
For SNM, the TL and the MFT are close around and below saturation density, but for PNM, the two differ



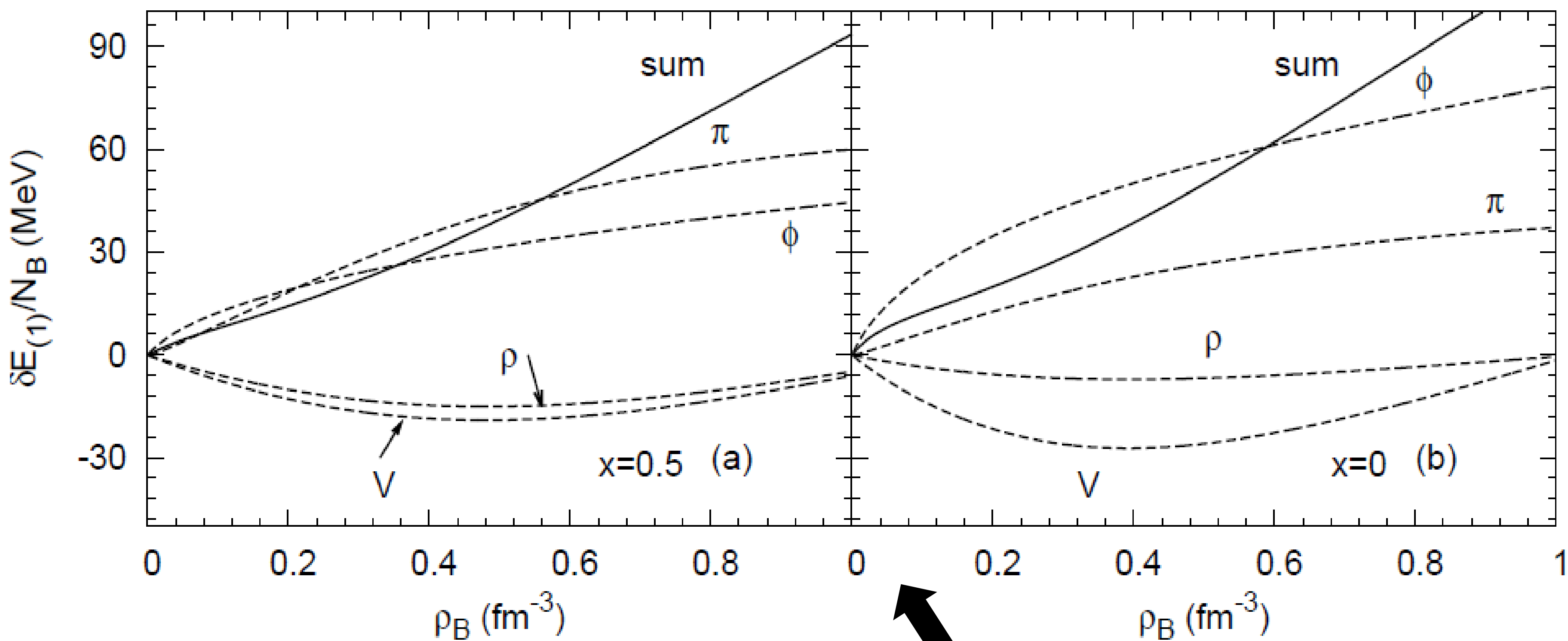
A. Akmal, *et.al.,* PRC **58**, 1804 (1998); P. Armani, *et.al.,* J. Phys. Conf. Ser. **336,** 012014 (2011); G. Wlazlowski, *et.al.,* PRL **113**, 182503 (2014); L. Coraggio, *et.al.,* PRC **87**, 014322 (2013); S. Gandolfi, *et.al.,* PRC **85**, 032801 (2012)



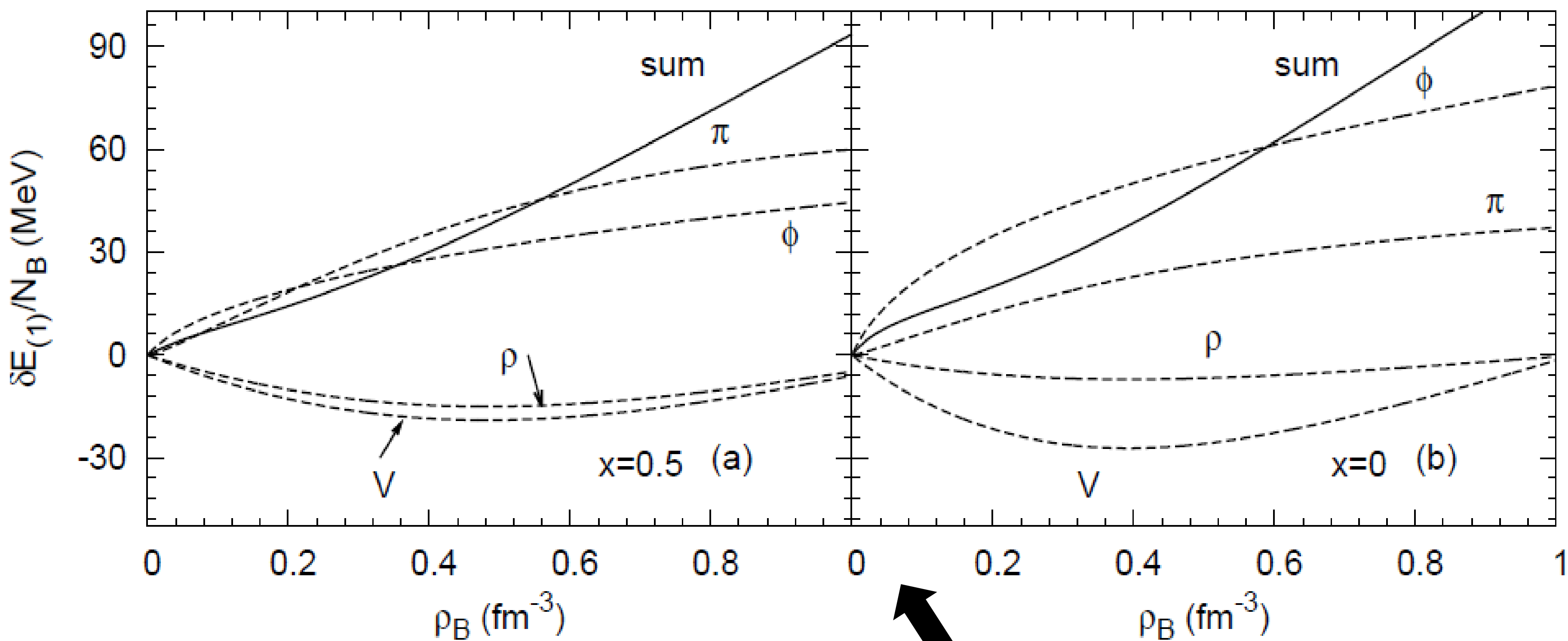
H. Muether, M. Prakash, and T. L. Ainsworth, PLB **199**, 469 (1987); E. N. E. van Dalen, C. Fuchs, and A. Faessler, PRC **72**, 065803 (2005); F. Sammarruca, B. Chen, L. Coraggio, N. Itaco, and R. Machleidt, PRC **86**, 054317 (2012).



90
60
30
0
-30
δE(1)/NB (MeV)
sum
π
ϕ
ρ
V
x=0.5
(a)
x=0
(b)
0
0.2
0.4
0.6
0.8
1
ρB (fm-3)



Strong cancellations among mesons



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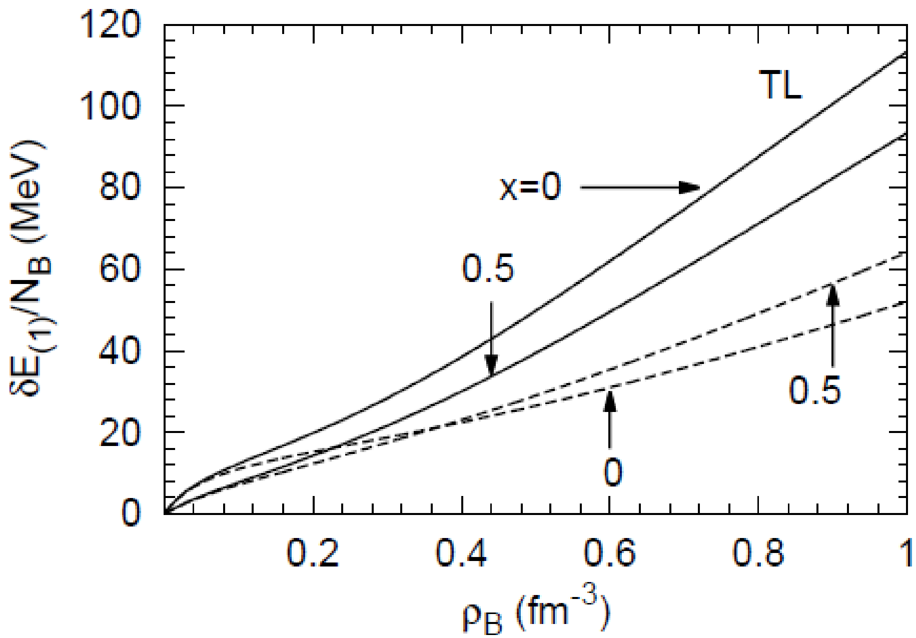
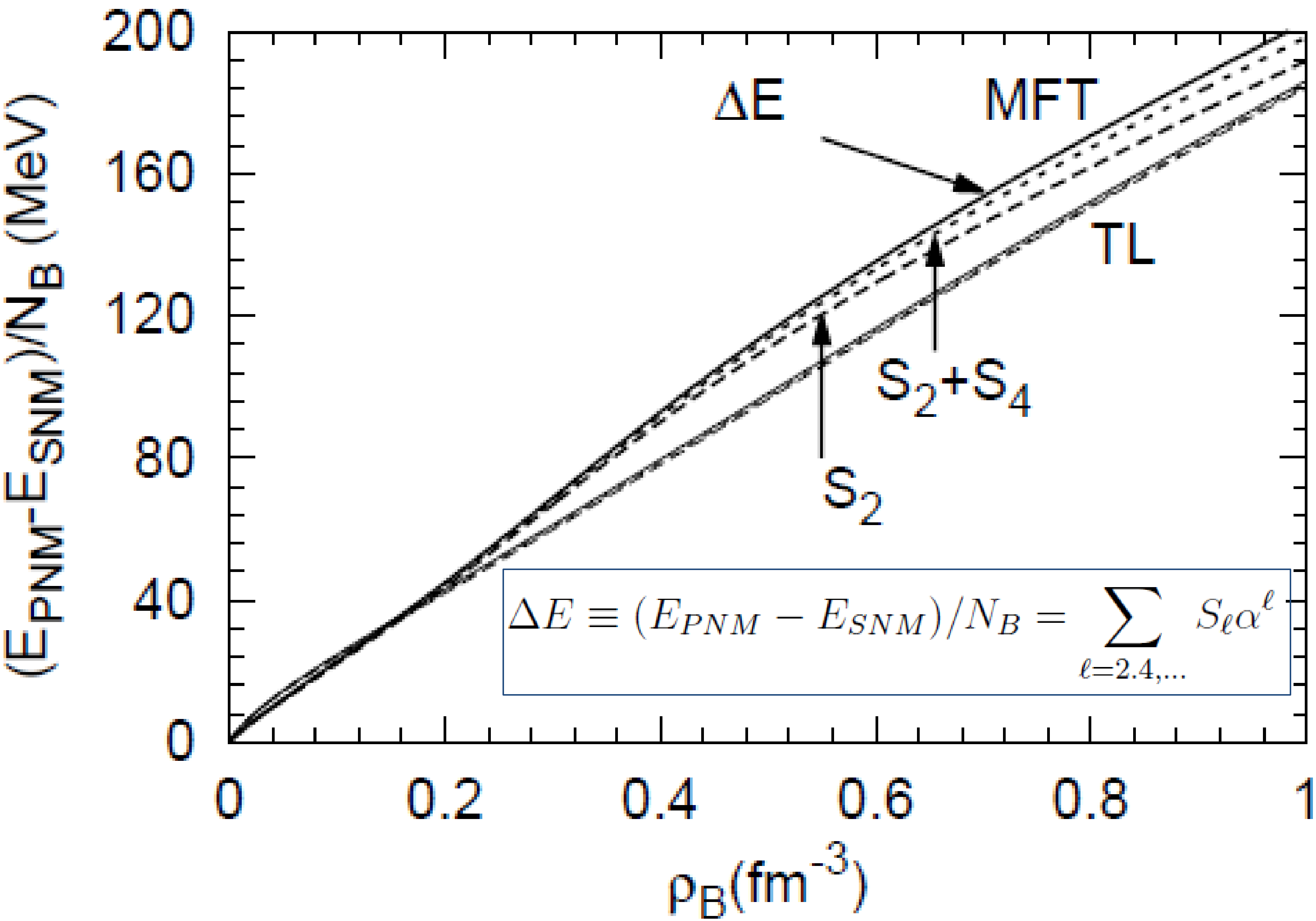
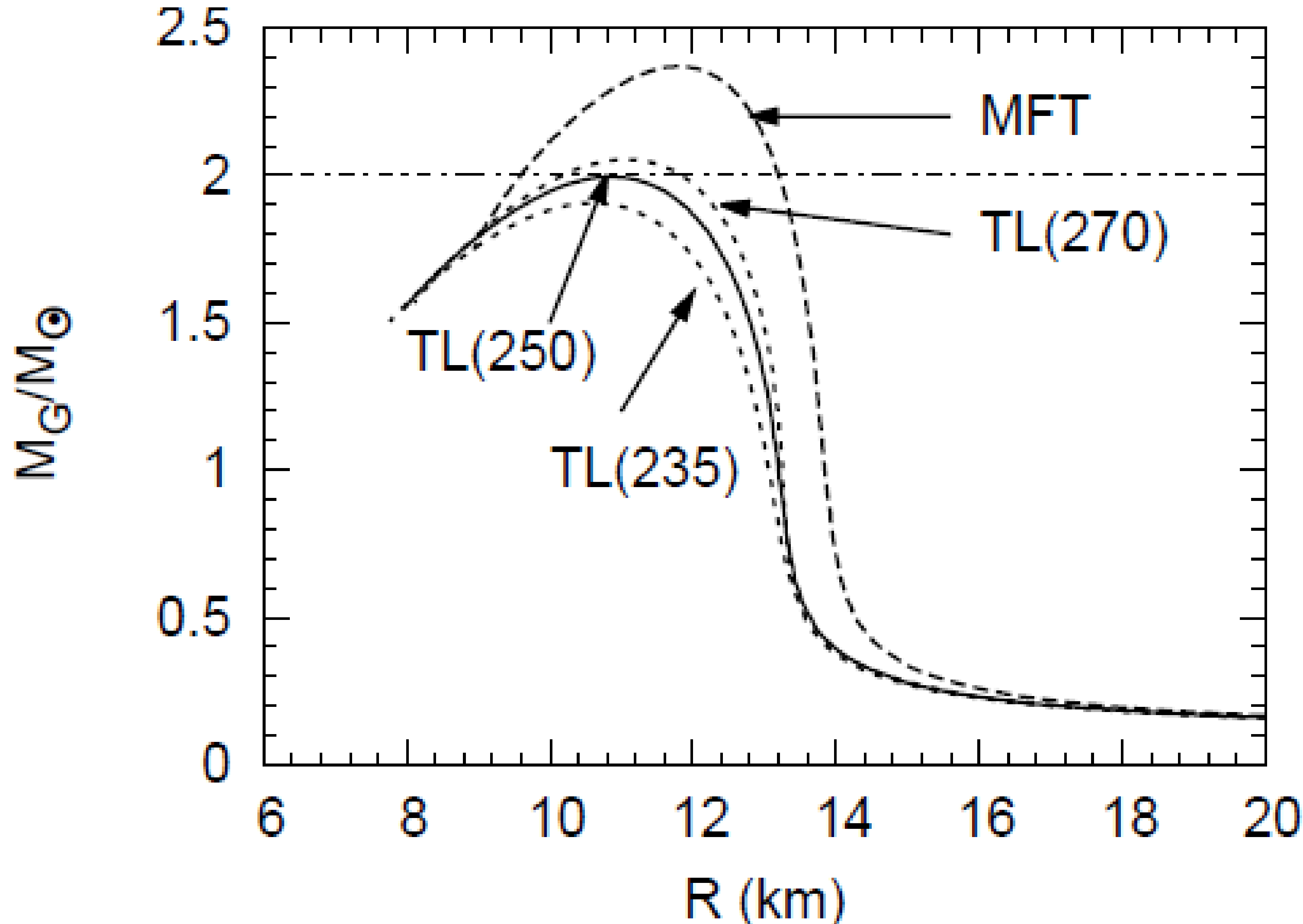


Nonrelativistic reduction of the full TL contributions

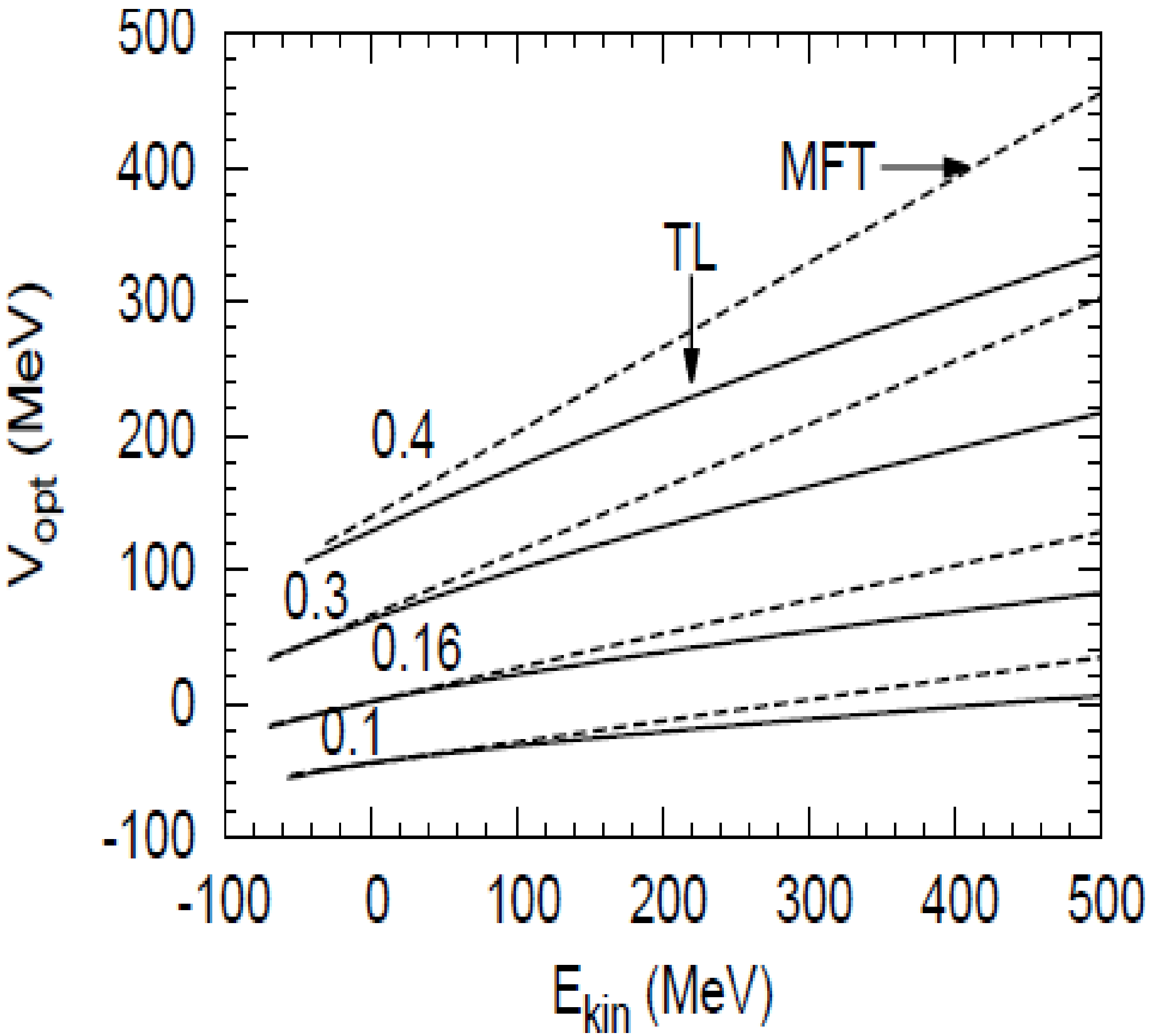


- Symmetry energy (S2) saturates the PNM and SNM energy difference
- The TL S2 is lower below saturation density and higher above the density than the MFT

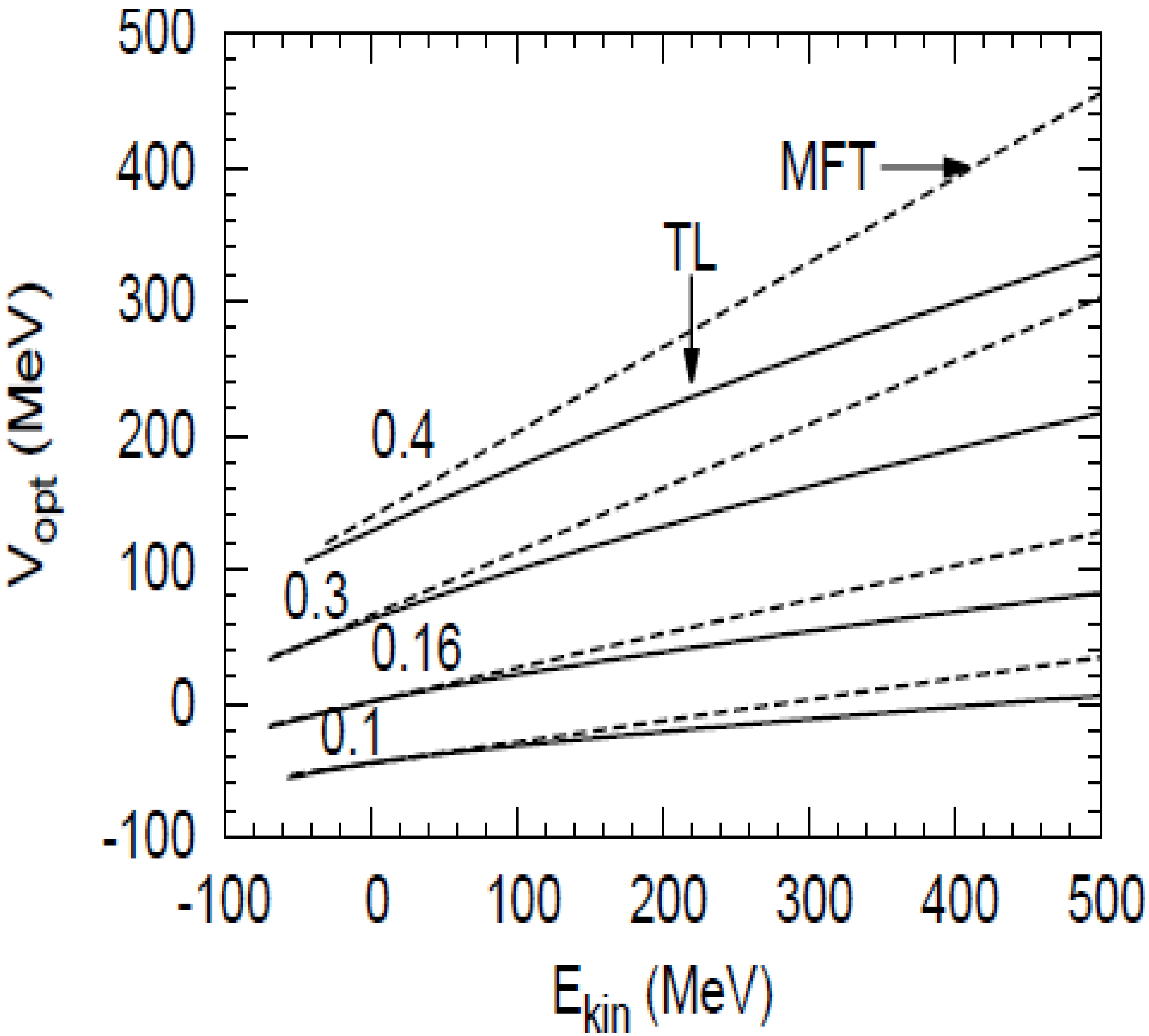


- Neutron star (NS) maximum mass observed: $2.01 \pm 0.04\ M_{\odot}, R_{max} = 11.0 \pm$1.0 km and $R_{1.4} = 11.5 \pm 0.7$ km
- Based on beta-equilibrium EOS

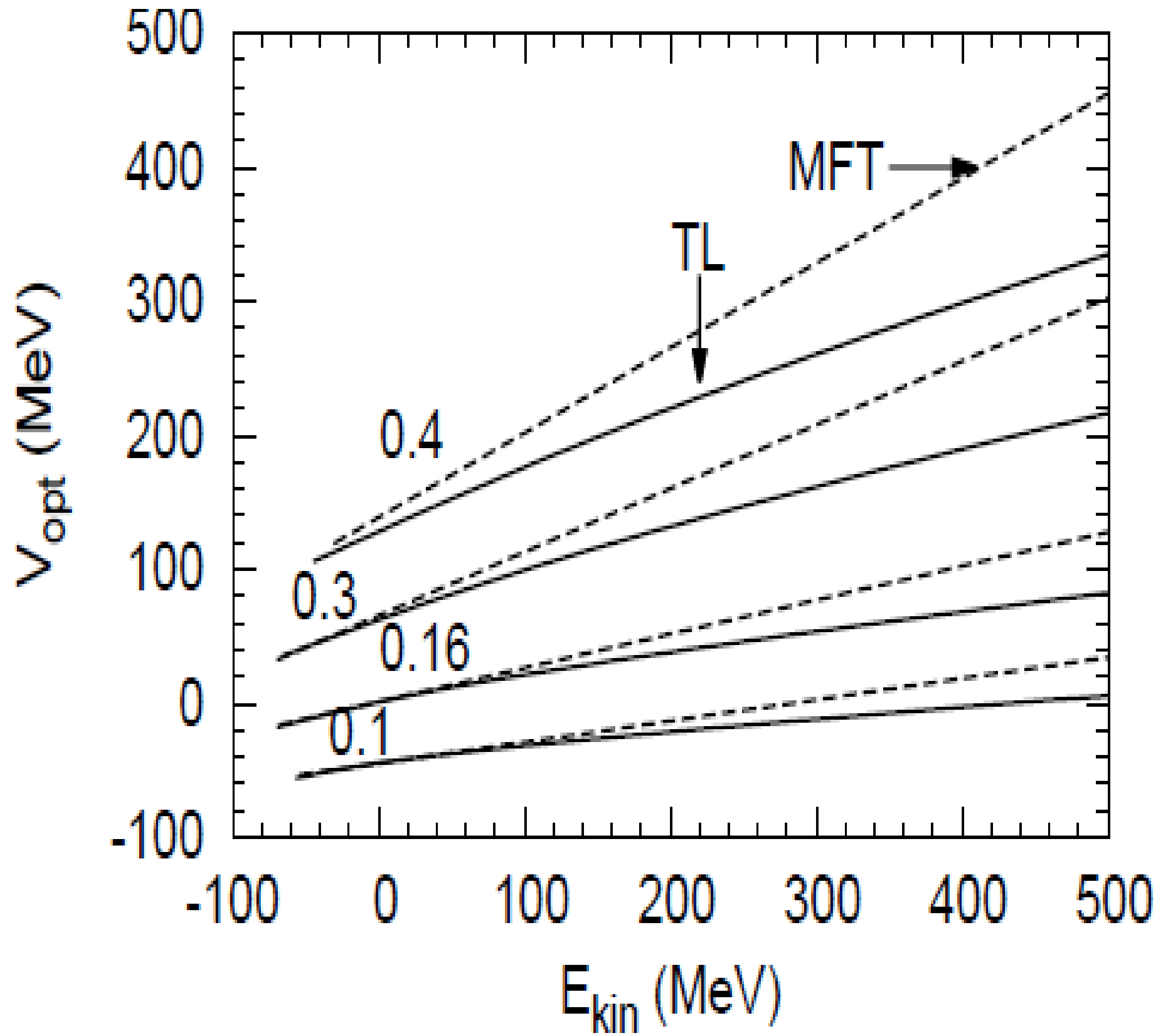
J. Antoniadis, et.al., Science **340**, 448 (2013)
J. M. Lattimer and M. Prakash, Phys. Rept **621**, 127 (2016)

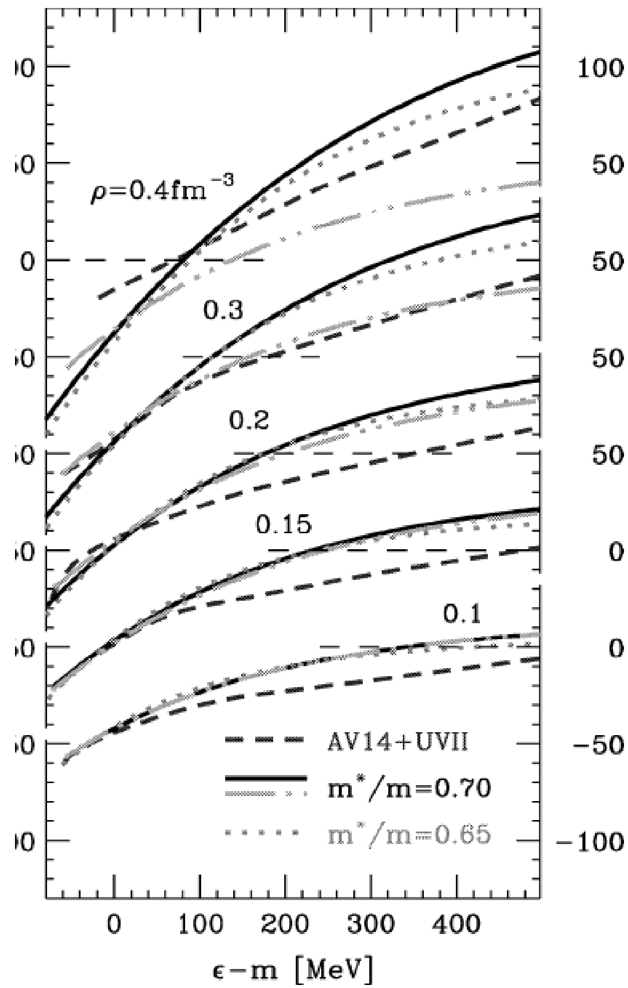


500
400
300
200
100
0
-100
V_{opt} (MeV)
-100
0
100
200
300
400
500
E_{kin} (MeV)
MFT
TL
0.4
0.3
0.16
0.1



- The MFT grows linearly with Ekin, much faster than the TL
- The TL agrees better with the microscopic calculation and extraction from medium-energy heavy-ion collisions





P. Danielewicz, NPA **673**, 375 (2000)

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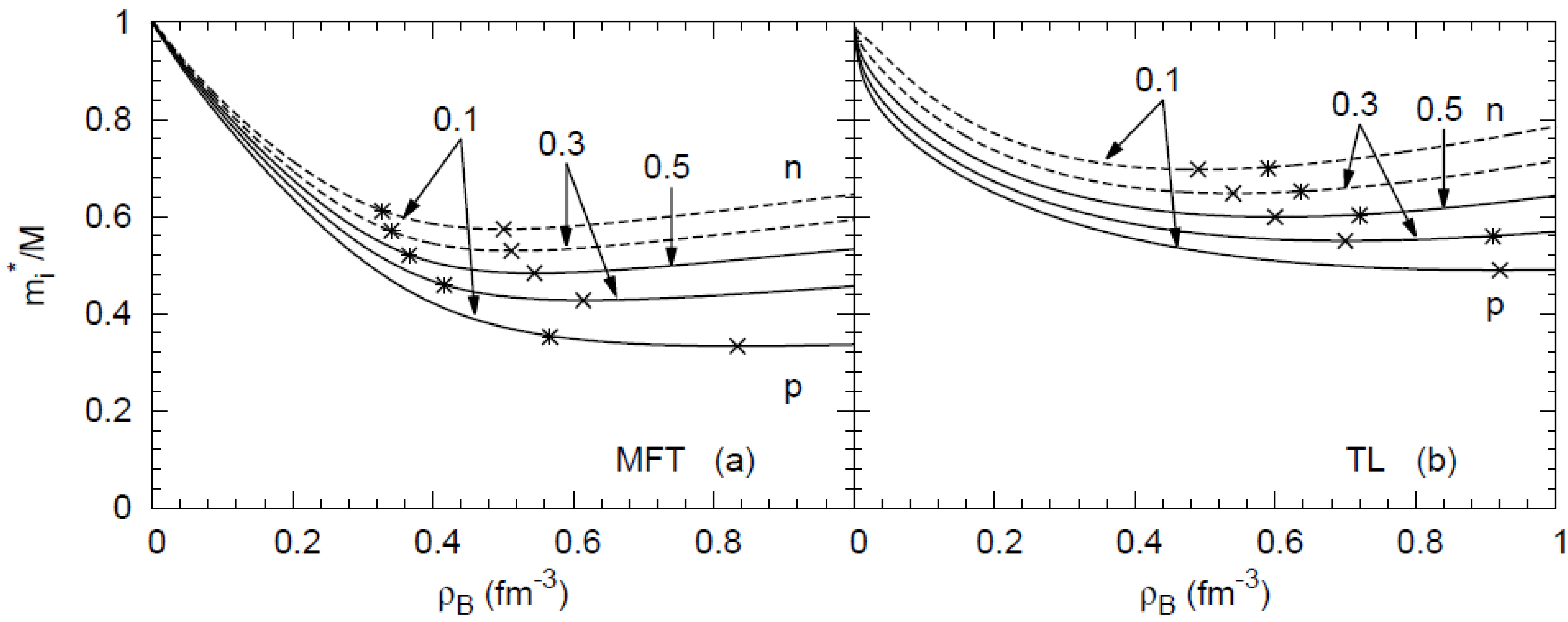
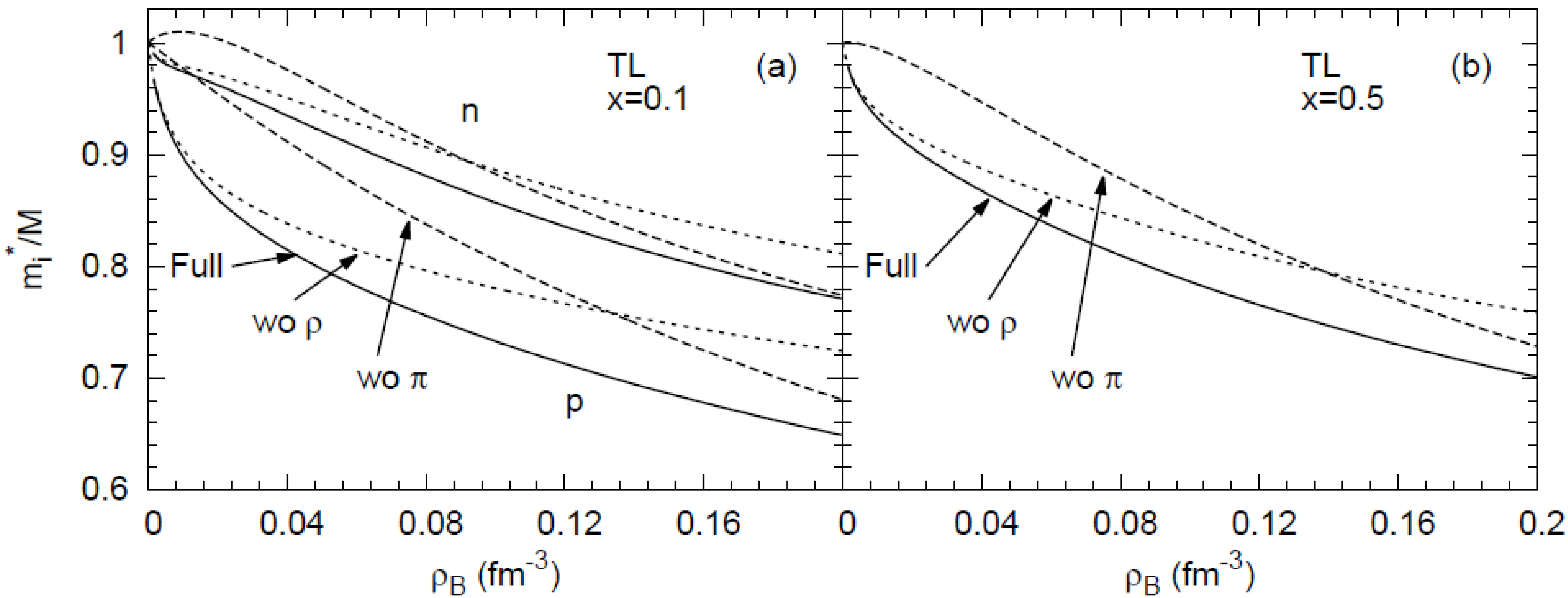
$$m_i^*(\rho_B, x) \equiv k_{F,i} \left(\frac{\partial \epsilon_i(k)}{\partial k} \right)^{-1} \Bigg|_{k=k_{F,i}}$$



- The TL Landau masses are larger than the MFTs
- At *-density, Fermi momentum =M^*.
- At x-density, Landau mass first derivative=0

Pion plays an important role in the low density behavior of the Landau mass



Finite T results

Formalisms: perturbative

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$$Z \equiv \mathrm{Tr}\, \exp\left[-\beta\left(H - \mu_p N_p - \mu_n N_n\right)\right] \equiv \exp\left[-\beta\Omega\left(T, V, \mu_{p,n}; \overline{\phi}, \overline{V}, \overline{b}\right)\right]$$

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$$\omega_{(1)}(T,\mu_{p,n}^{(0)};bg) = \omega_{(0)}(T,\mu_{p,n}^{(0)};bg) + \delta\omega_{(1)}(T,\nu_{p,n};\overline{\phi})$$

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At given T and density, bg minimizes free energy

Formalisms: self-consistent

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$$\epsilon_i\left[p; bg, n_{p,n}\left(k\right)\right] = \epsilon_{(0),i}(p; bg) + \delta\epsilon_{(1),i}\left[p; bg, n_{p,n}\left(k\right)\right]$$

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$$\mathcal{F}\left[T, bg, n_{p,n}(k)\right] = \mathcal{E}\left[bg, n_{p,n}(k)\right] - T\mathcal{S}\left[bg, n_{p,n}(k)\right]$$

Formalisms: self-consistent

$$\epsilon_i\left[p; bg, n_{p,n}(k)\right] = \epsilon_{(0),i}(p; bg) + \delta\epsilon_{(1),i}\left[p; bg, n_{p,n}(k)\right]$$

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At given T and density, bg minimizes free energy

At MFT level, this approach is the same as the perturbative one.
At two-loop level, they are different.

Landau’s Fermi liquid theory

In the degenerate limit,

Landau's Fermi liquid theory

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$$\mathcal{S} = \frac{\pi^2}{3} T \sum_i N_i(0) \qquad \left[\, N_i(0) = \gamma_s \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \delta\left(\epsilon_i\left(k\right) - \mu_i\right) \,\right]$$

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$$\frac{E_{th}}{N_B} = \frac{T^2}{\rho_B} \sum_i a_i \rho_i \qquad \left[\, Q_{\rm th} \equiv Q(\rho_B, x, T) - Q(\rho_B, x, T=0) \,\right]$$

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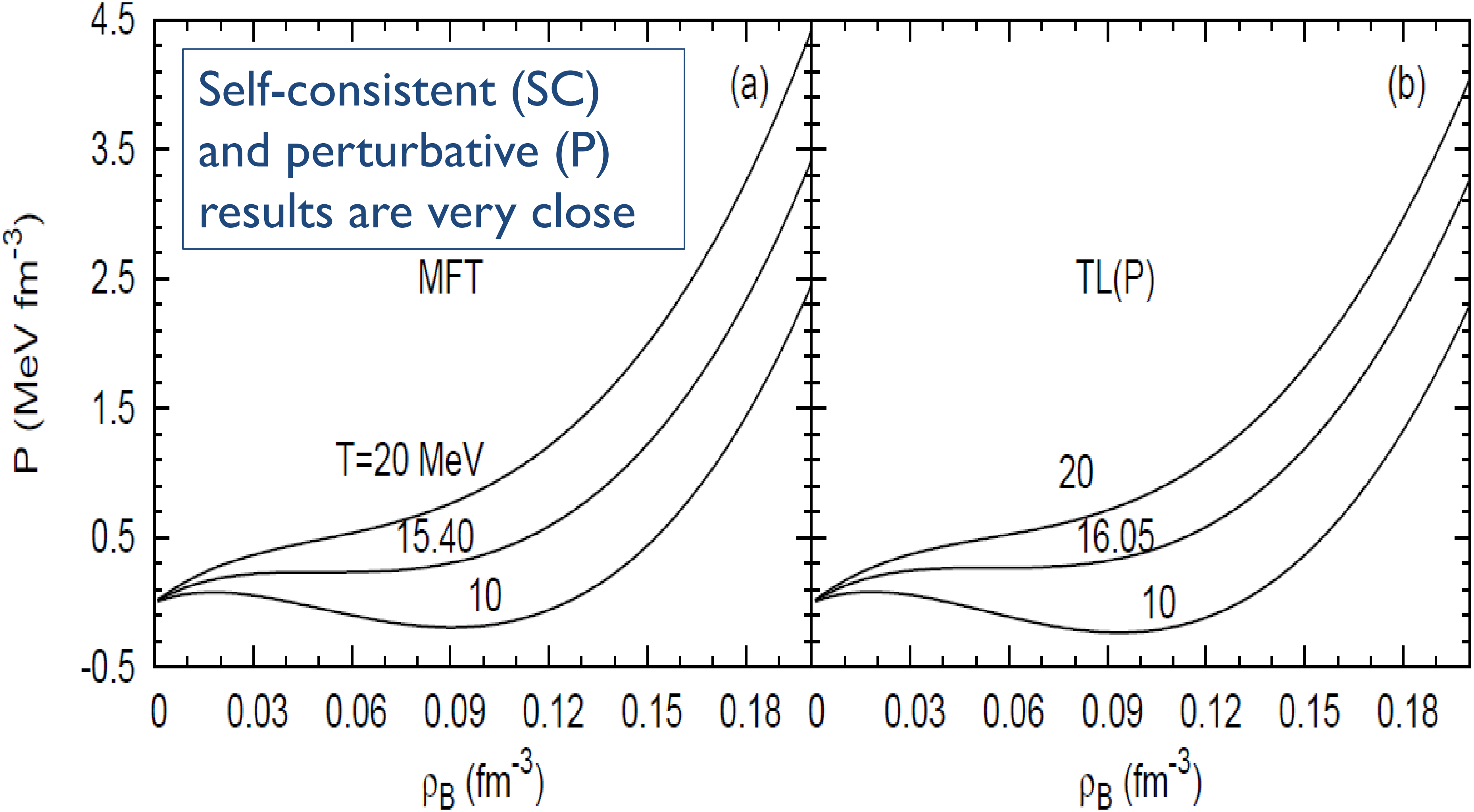
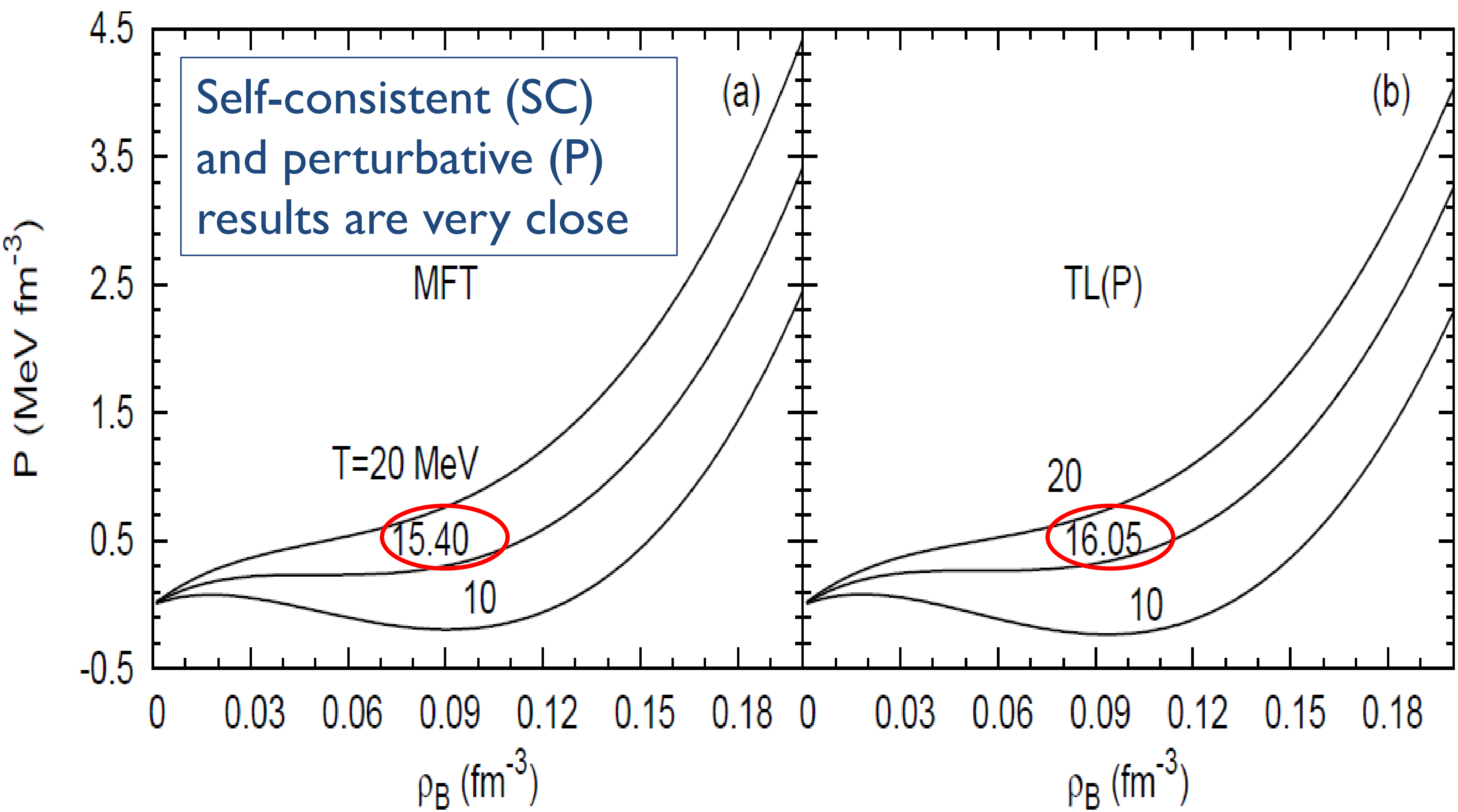
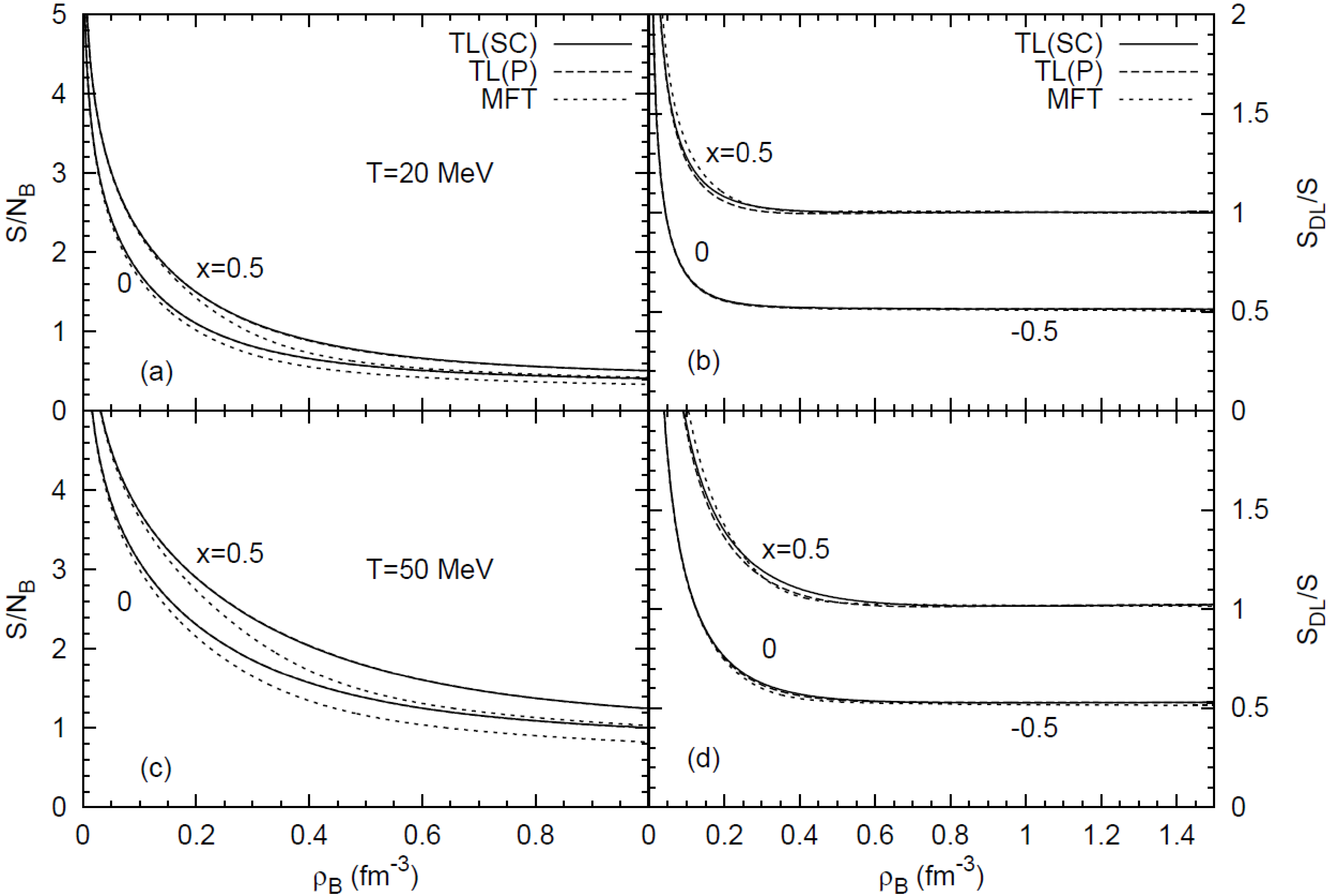
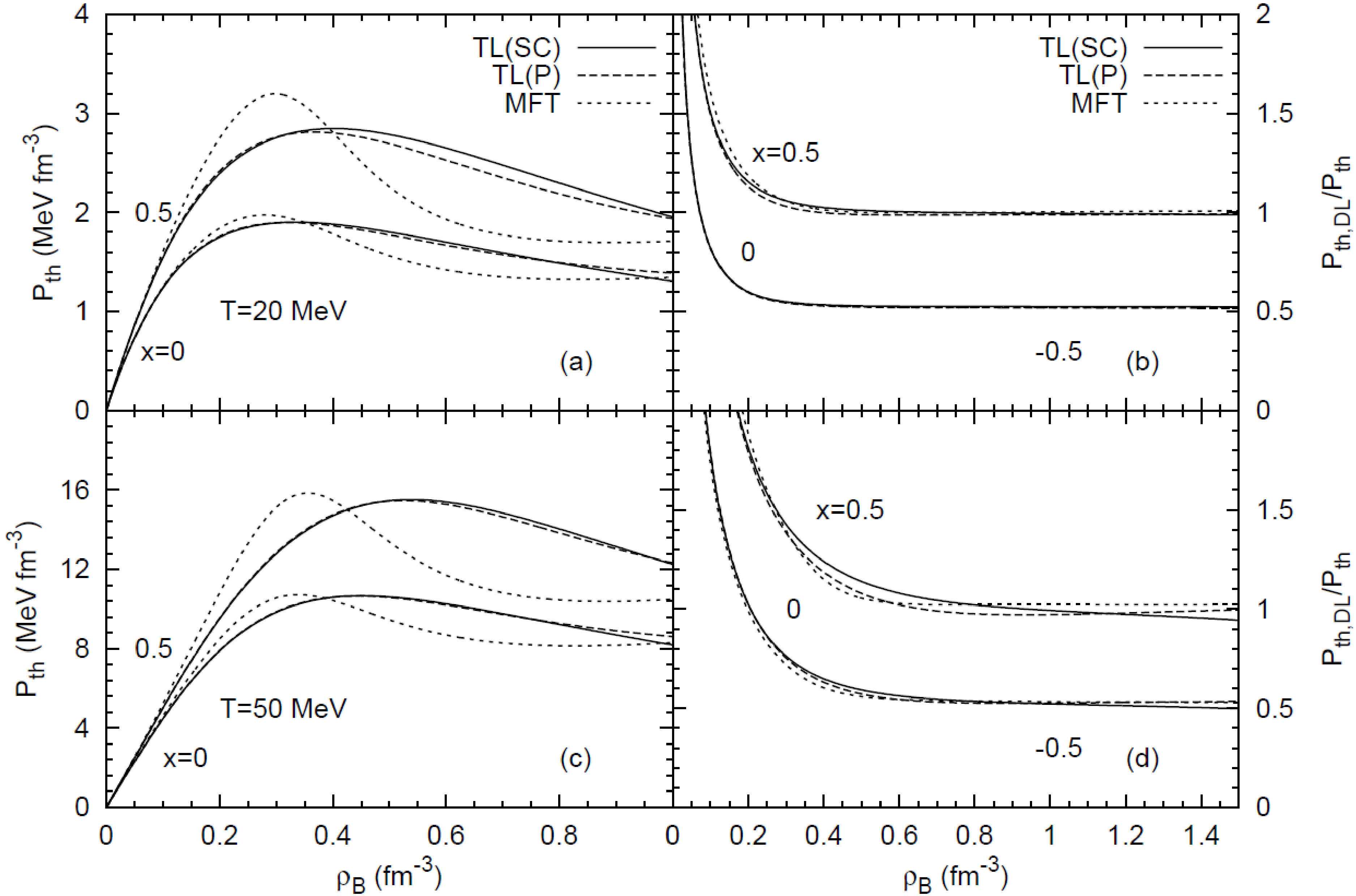
A good way to test our calculation


Self-consistent (SC) and perturbative (P) results are very close
P (MeV fm^{-3})
(a)
MFT
T=20 MeV
15.40
10
(b)
TL(P)
20
16.05
10
ρ_B (fm^{-3})
ρ_B (fm^{-3})
4.5
3.5
2.5
1.5
0.5
-0.5
0
0.03
0.06
0.09
0.12
0.15
0.18



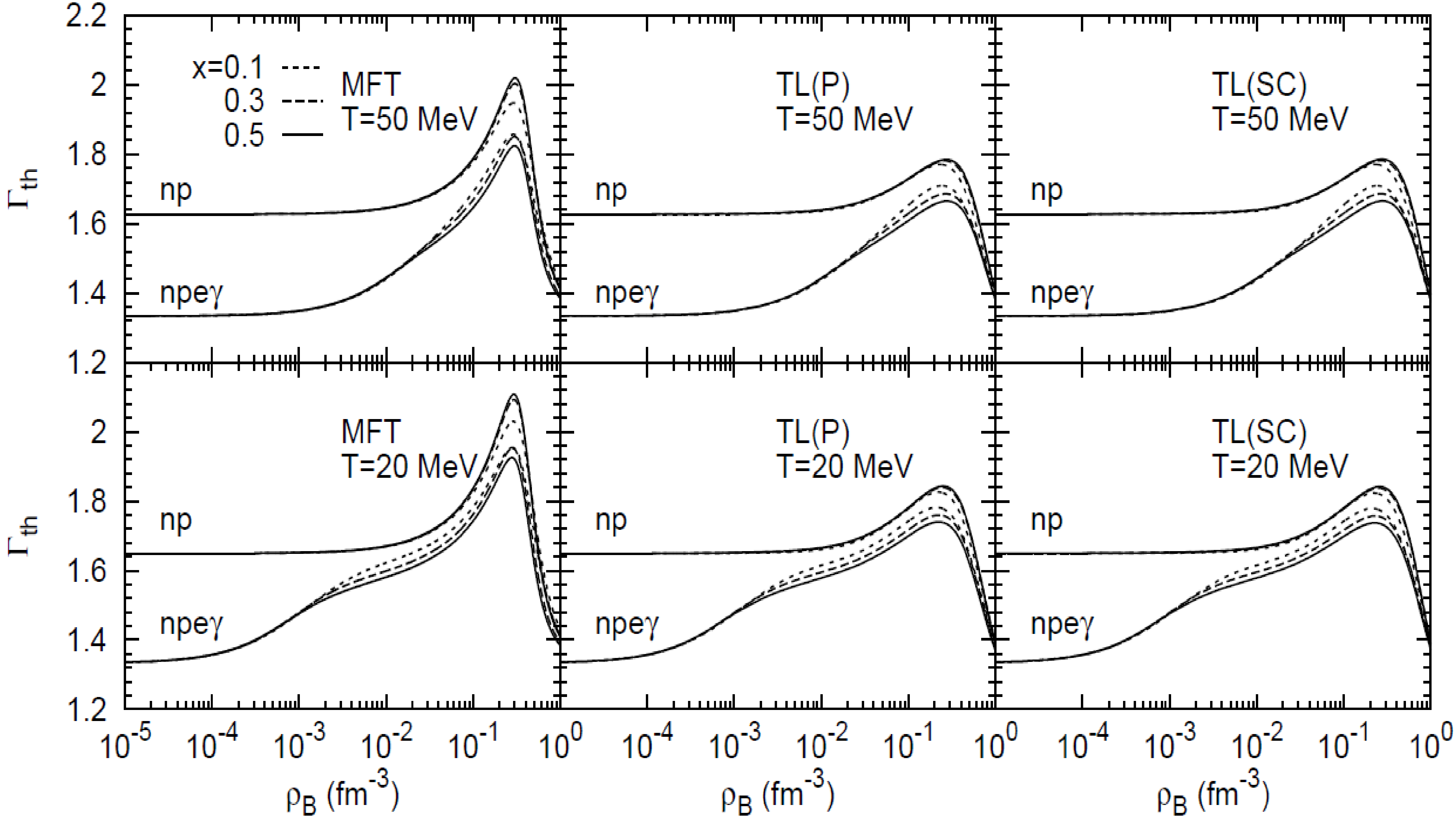
Critical temperatures


TL(SC)
TL(P)
MFT
T=20 MeV
T=50 MeV
x=0.5
0
-0.5
(a)
(b)
(c)
(d)
S/N_B
S_DL/S
ρ_B (fm^-3)



SC and P differ by less than 3%. MFT has a characteristic bump at 0.3 fm^-3.

$$\Gamma_{\rm th} \equiv 1 + \frac{P_{\rm th}}{\mathcal{E}_{\rm th}}$$



The SC and P results are different from the MFT: no bump!

Low density limits: non-relativistic and relativistic gas

Summary

- Including TL contribution to the MFT terms improves PNM EOS at sub-nuclear density
- TL softens EOS, but supports 2-solar mass neutron star
- TL improves nucleon optical potential
- TL's impacts on zero and finite-T bulk properties are significant
- Improved relativistic calculations can extrapolate the constrained EOS to high density region

Back up

Fix couplings

$$m_i^* = E_{F,i}^*$$

$$M_0^* = \sqrt{m_0^{*2} - k_{F0}^2} = 0.674M$$

$$\mu_0 - E_{F0}^* = \frac{g_v^2}{m_v^2}\rho_0 \quad \text{with} \quad E_{F0}^* = \sqrt{k_{F0}^2 + M_0^{*2}}$$

$$S_{2,0} - \frac{k_{F0}^2}{6E_{F0}^*} = \frac{\rho_0}{8}\frac{g_\rho^2}{m_\rho^2}$$

$$M - B_0 - \frac{\mathcal{E}_{kin0}}{\rho_0} = \frac{\mathcal{V}(\overline{\phi}_0)}{\rho_0} + \frac{1}{2}\frac{g_v^2}{m_v^2}\rho_0$$

$$\frac{1}{g_s\overline{\phi}_0}\frac{\rho_{s,0}}{m_s^2} = \frac{1}{g_s^2} + \frac{\kappa_3}{g_s^2}\frac{1}{2}\frac{g_s\overline{\phi}_0}{M} + \frac{\kappa_4}{g_s^2}\frac{1}{6}\left(\frac{g_s\overline{\phi}_0}{M}\right)^2$$

$$K_{v,0} - 3\frac{k_{F0}^2}{E_{F0}^*} = 9\rho_0\left[\frac{g_v^2}{m_v^2} + \frac{M_0^*}{E_{F0}^*}\left.\frac{\partial M^*}{\partial \rho_B}\right|_{x=0.5}\right]$$

Fix couplings

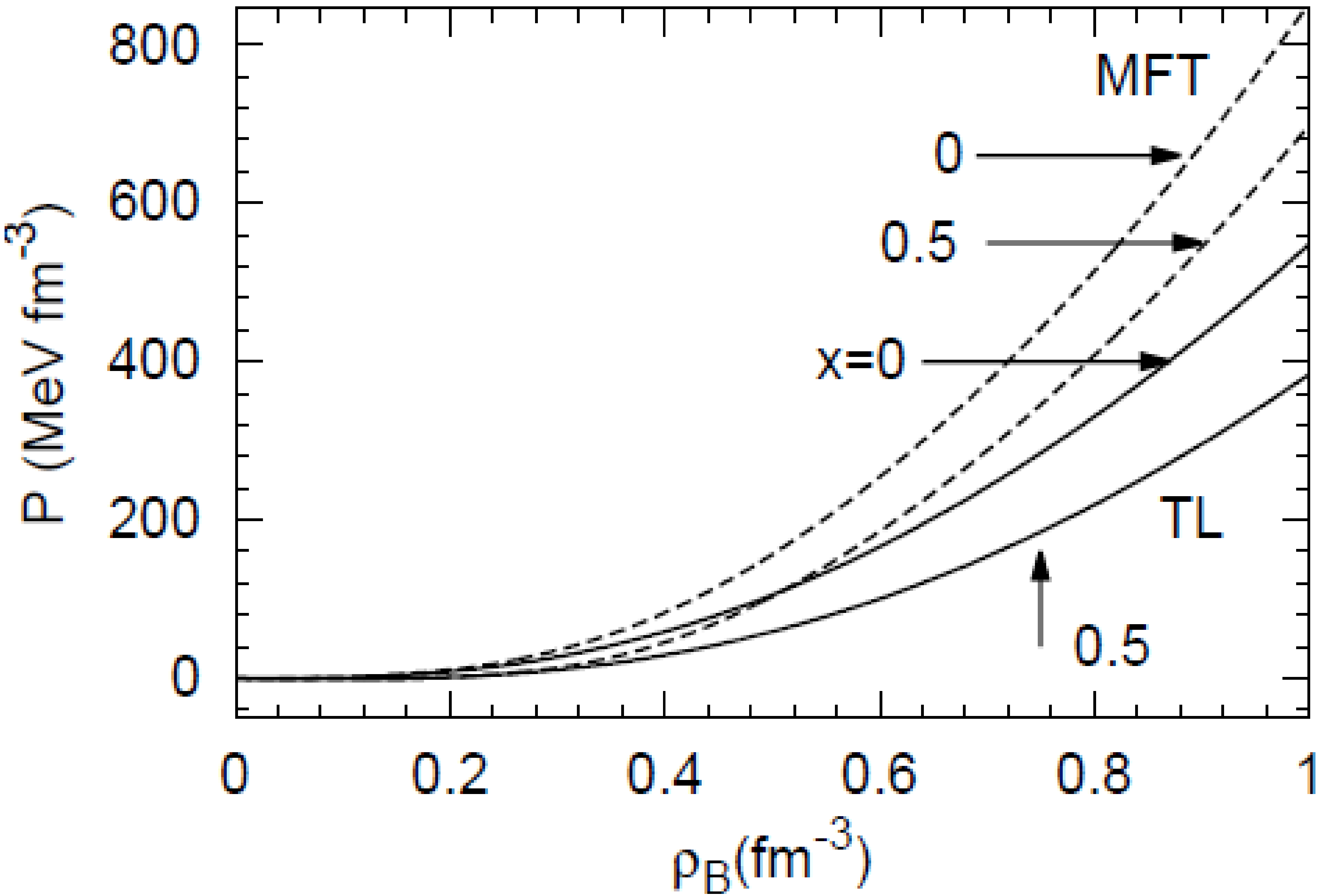
$$\mu_0 - E^*_{F0} = \frac{g_v^2}{m_v^2}\rho_0 + \left.\frac{\partial \delta\mathcal{E}_{(1)}}{\partial \rho_B}\right|_{\overline{\phi}_0, x=0.5}$$

$$S_{2,0} - \frac{k_{F0}^2}{6E^*_{F0}} = \frac{\rho_0}{8}\frac{g_\rho^2}{m_\rho^2} + \delta S_{2,(1)}$$

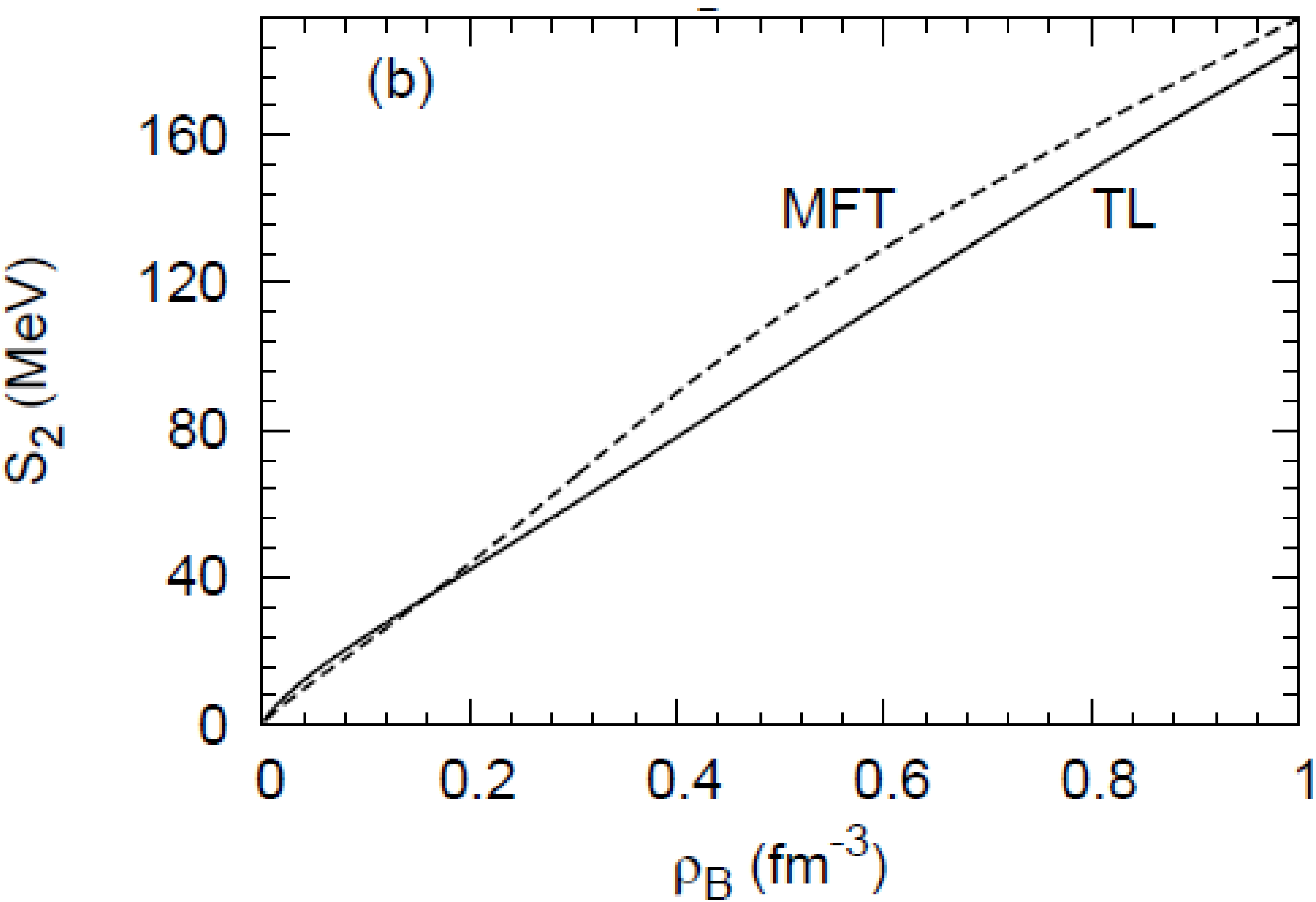
$$M - B_0 - \frac{\mathcal{E}_{kin0}}{\rho_0} = \frac{\mathcal{V}(\overline{\phi}_0) + \delta\mathcal{E}_{(1)}}{\rho_0} + \frac{1}{2}\frac{g_v^2}{m_v^2}\rho_0$$

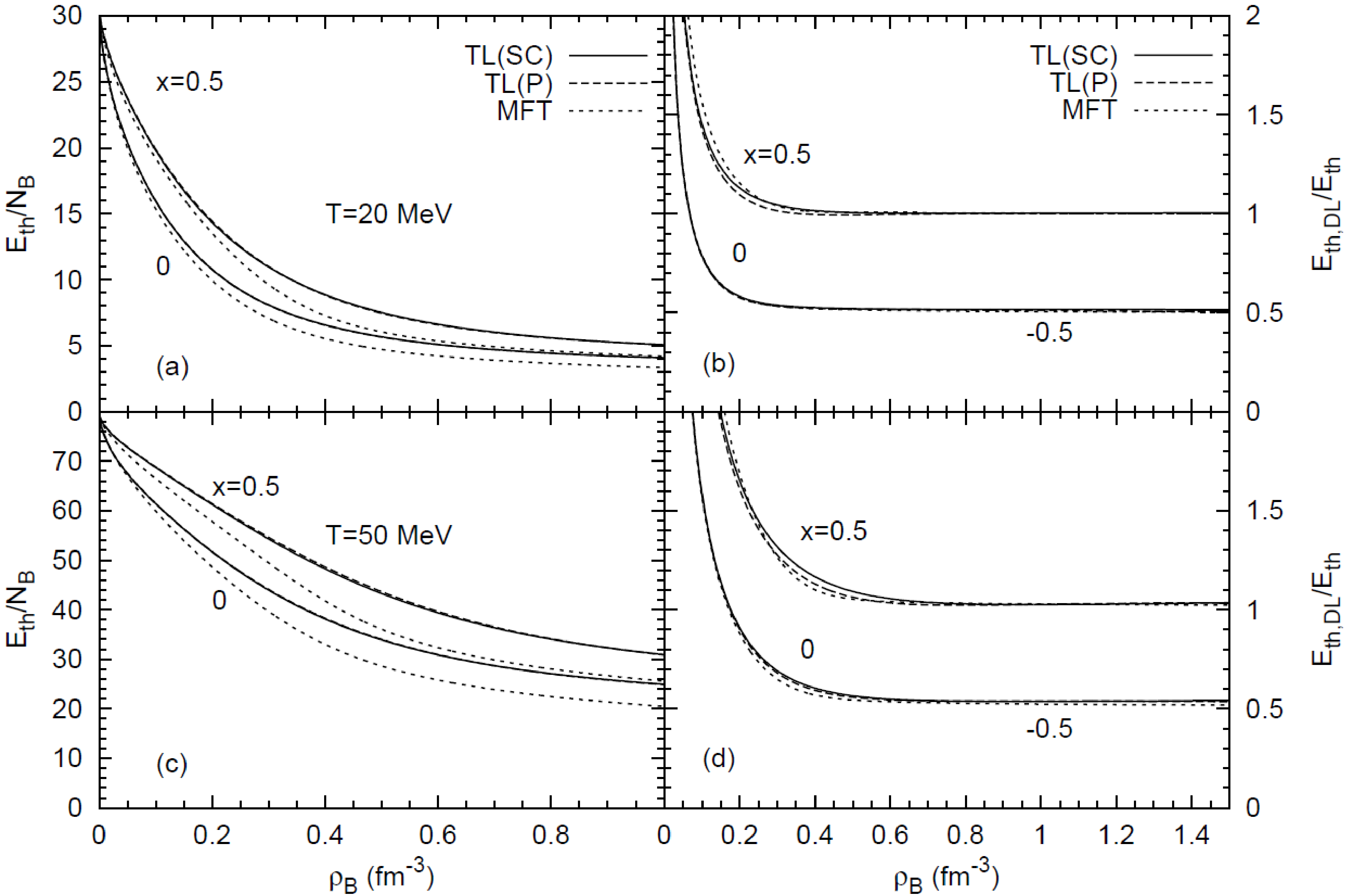
$$K_{v,0} - 3\frac{k_{F0}^2}{E^*_{F0}} = 9\rho_0\left[\frac{g_v^2}{m_v^2} + \frac{M_0^*}{E^*_{F0}}\left.\frac{\partial M^*}{\partial \rho_B}\right|_{x=0.5}\right] + \delta K_{v,(1)}$$

$$\frac{E^*_{F0}}{m_0^*} = 1 + \frac{E^*_{F0}}{k_{F0}}\left.\frac{\partial \delta\epsilon_{(1)}(k)}{\partial k}\right|_{k=k_{F0}} ,$$

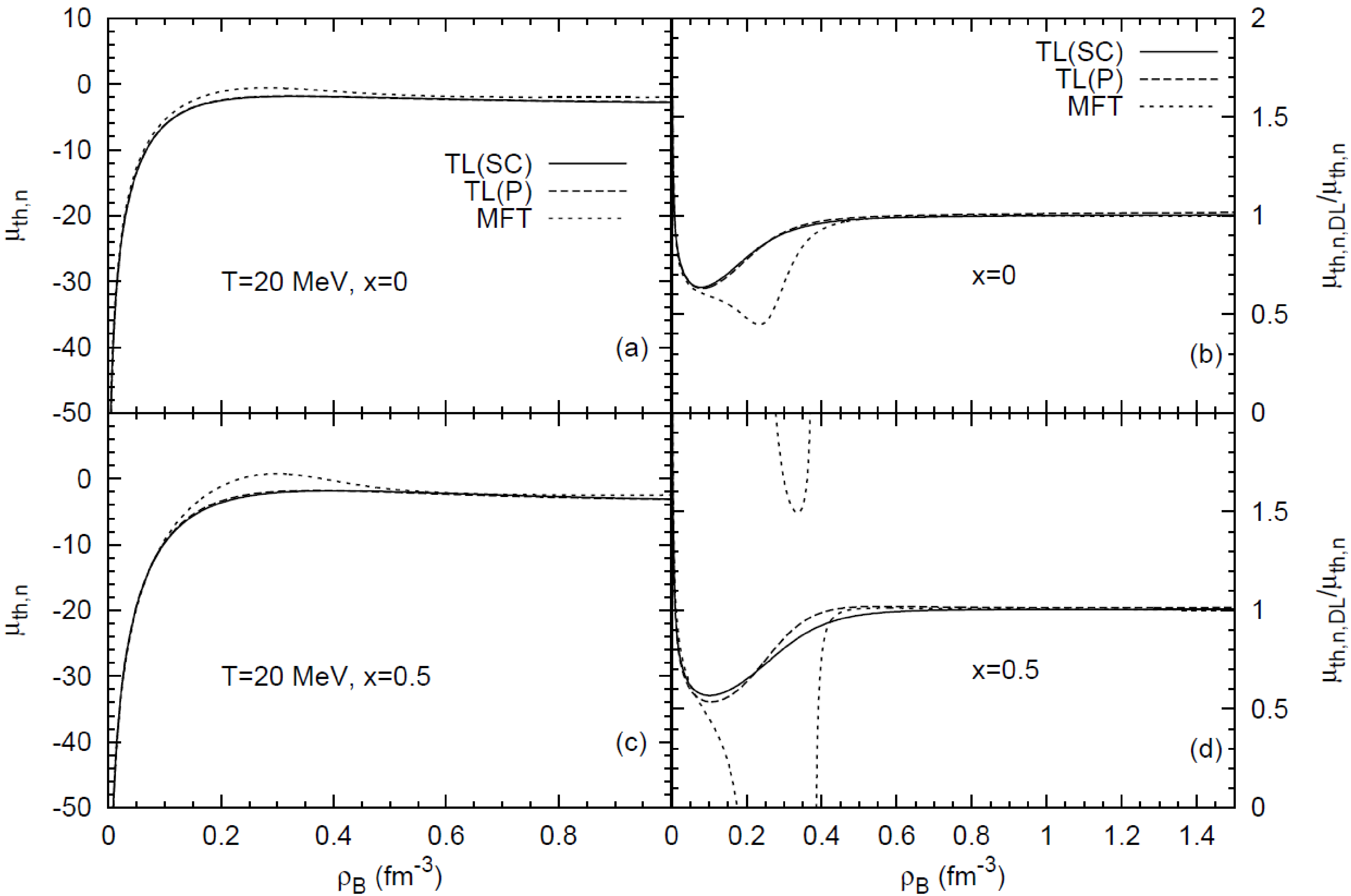


800
600
400
200
0
P (MeV fm-3)
MFT
0
0.5
x=0
TL
0.5
0
0.2
0.4
0.6
0.8
1
ρB(fm-3)


(b)
MFT
TL
S2 (MeV)
0
40
80
120
160
0
0.2
0.4
0.6
0.8
1
ρB (fm-3)



TL(SC)
TL(P)
MFT
x=0.5
T=20 MeV
0
(a)
(b)
-0.5
T=50 MeV
(c)
(d)
E_{th}/N_B
$E_{th,DL}/E_{th}$
ρ_B (fm^{-3})



TL(SC)
TL(P)
MFT
T=20 MeV, x=0
(a)
x=0
(b)
T=20 MeV, x=0.5
(c)
x=0.5
(d)
μth,n
μth,n,DL/μth,n
ρB (fm-3)