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# Composition and Structure of Protoneutron Stars with the Brueckner-Bethe-Goldstone theory

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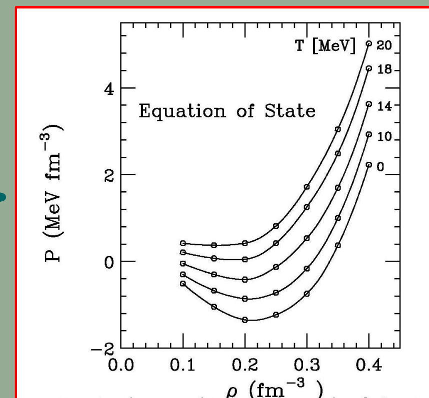
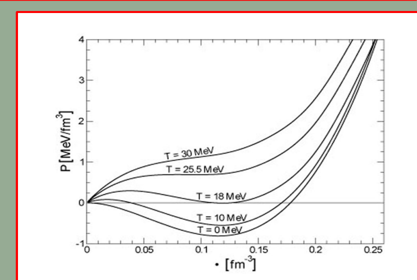
# EoS of nuclear matter at finite T

Van der Waals behavior.
Liquid-gas phase transition with critical temperature $T_c$~18-20 MeV.

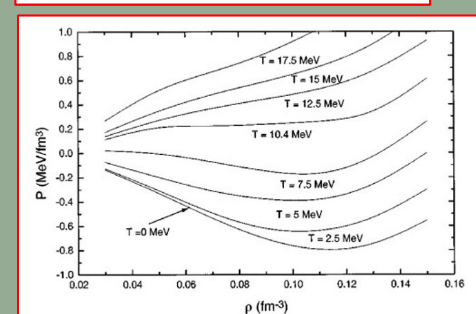
- Variational — B. Friedman & V. R. Pandharipande, Nucl. Phys. A361, 502 (1981)
- BHF — M. Baldo & L. Ferreira, PRC59, 682 (1999)




- Chiral Perturbation — S.Fritsch, N.Kaiser, W.Weise, PLB 545, 73 (2002)



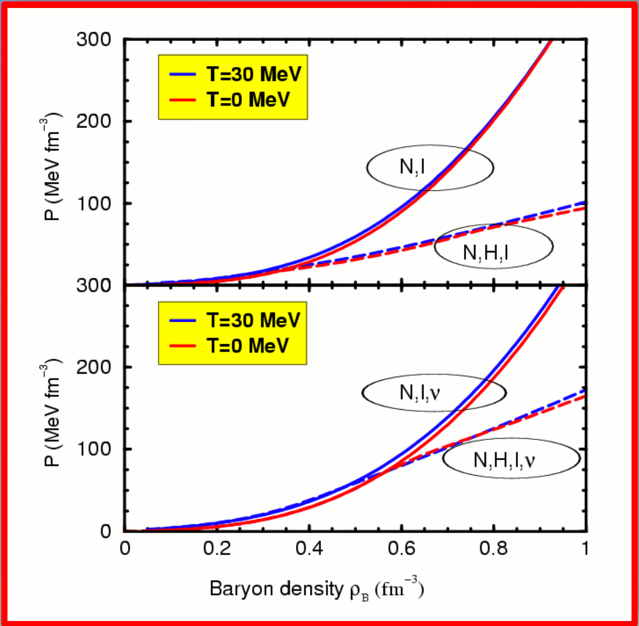

- DBHF — B. Ter Haar & R. Malfliet Phys.Rep. 149, 207 (1987); H.Huber, F.Weber, M.K.Weigel PRC 57,3484,(1998)



# BHF EoS at finite temperature

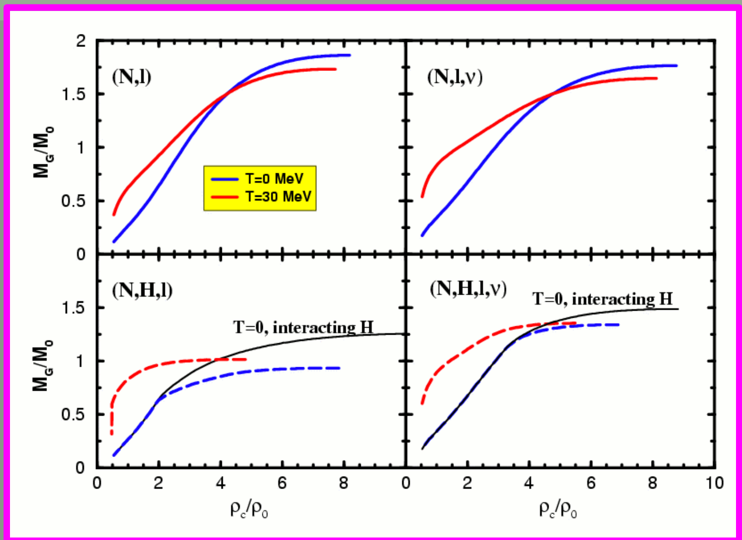
- **Finite Temperature BHF (Brueckner-Hartree-Fock)**
  - Bloch-De Dominicis formulation

    (Nucl. Phys. **10**, 509 (1959) and refs. therein)
- **Two- & three-body interaction**
  - Argonne v18: modern parametrization of the N-N scattering phase shifts (Wiringa 1995).
  - Phenomenological Urbana model for TBF (Carlson 1983)
- **Inclusion of free hyperons**




- Weak thermal effects.
- Neutrinos soften the EoS.
- Additional softening due to H , less dramatic than in the neutrino-free case.

After solving TOV…

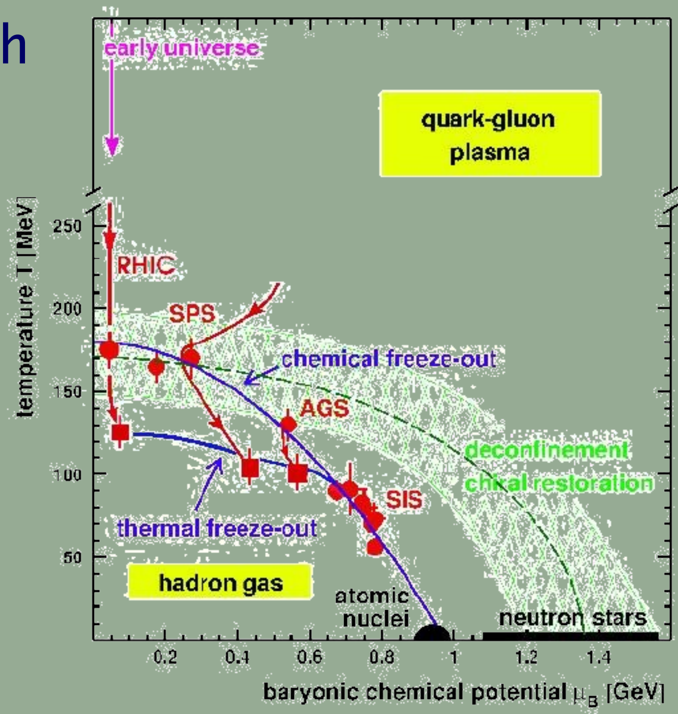



| Composition | $T$ (MeV) | $M/M_\odot$ | $R$ (km) | $\rho_c/\rho_0$ |
|---|---|---|---|---|
| $N, l$ | 0 | 1.86 | 9.5 | 8.2 |
| | 10 | 1.82 | 9.5 | 8.1 |
| | 30 | 1.73 | 9.7 | 7.7 |
| $N, l, \nu$ | 0 | 1.76 | 9.1 | 8.8 |
| | 10 | 1.75 | 9.2 | 8.5 |
| | 30 | 1.65 | 9.5 | 8.1 |
| $N, H_{free}, l$ | 0 | 0.93 | 10.2 | 7.8 |
| | 10 | 0.95 | 11.0 | 6.7 |
| | 30 | 1.00 | 13.0 | 4.8 |
| $N, H_{int.}, l$ | 0 | 1.25 | 8.8 | 11.5 |
| $N, H_{free}, l, \nu$ | 0 | 1.34 | 10.6 | 6.9 |
| | 10 | 1.35 | 11.0 | 6.1 |
| | 30 | 1.35 | 12.2 | 5.5 |
| $N, H_{int.}, l, \nu$ | 0 | 1.48 | 9.6 | 8.8 |

**Reduction of the maximum mass down to about 1.25 (1.5) Mo for NS (PNS)**

# Including Quark Matter

- Since we have no theory which describes both confined and deconfined phases, we use two separate EOS.




**Quark matter models :** MIT Bag Model,
Nambu-Jona-Lasinio (NJL)

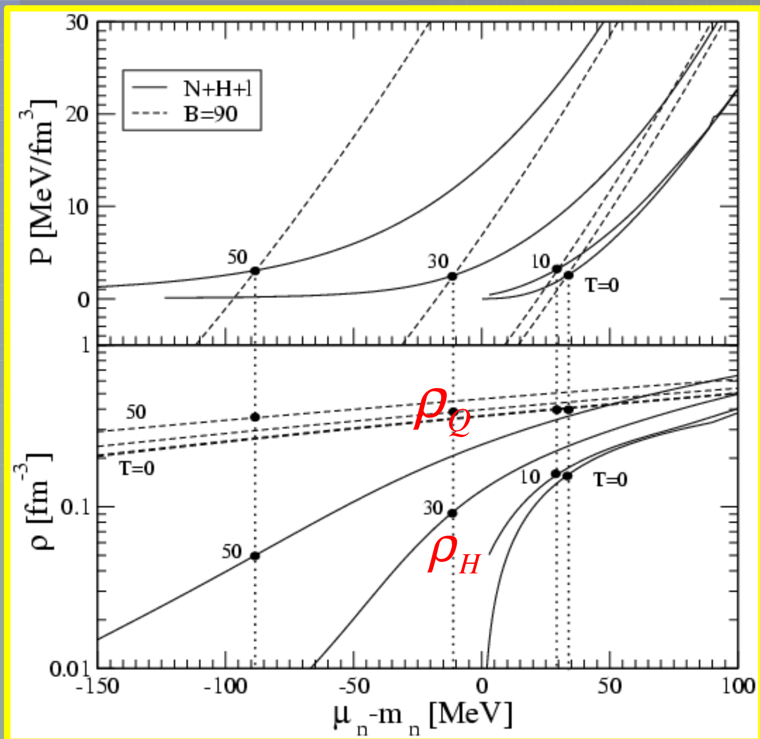
Evidence of a first order phase transition (Fodor&Katz 2004)

Maxwell construction

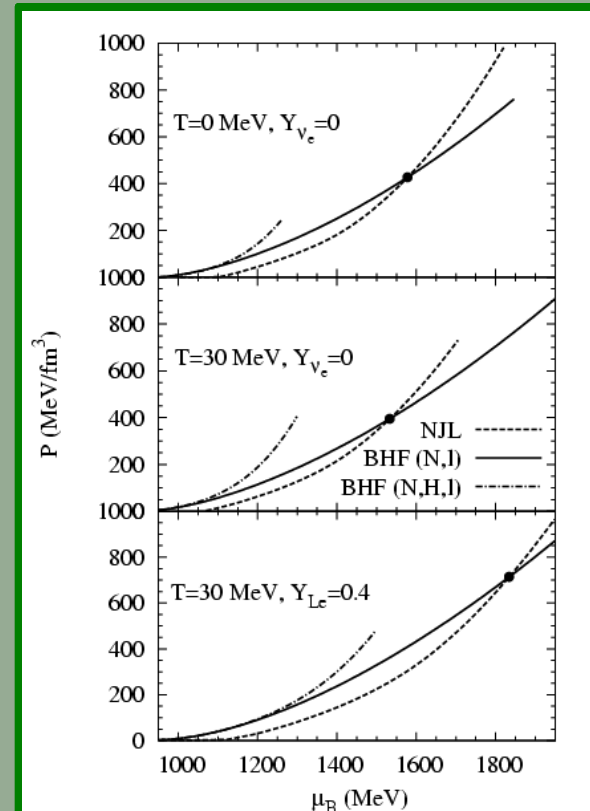
$$\mu_H = \mu_Q = \mu$$
$$p_H(\mu) = p_Q(\mu) = p$$
$$T_H = T_Q$$

# Maxwell construction

## MIT bag



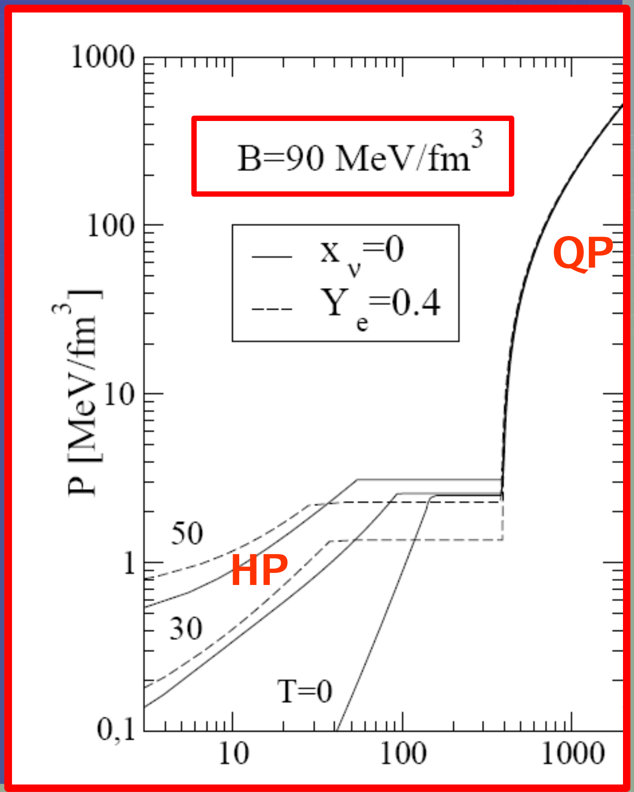

## NJL




- Low transition density in the hadron phase
- Decreasing values of the transition density with increasing T
- Similar behavior with a density dependent B

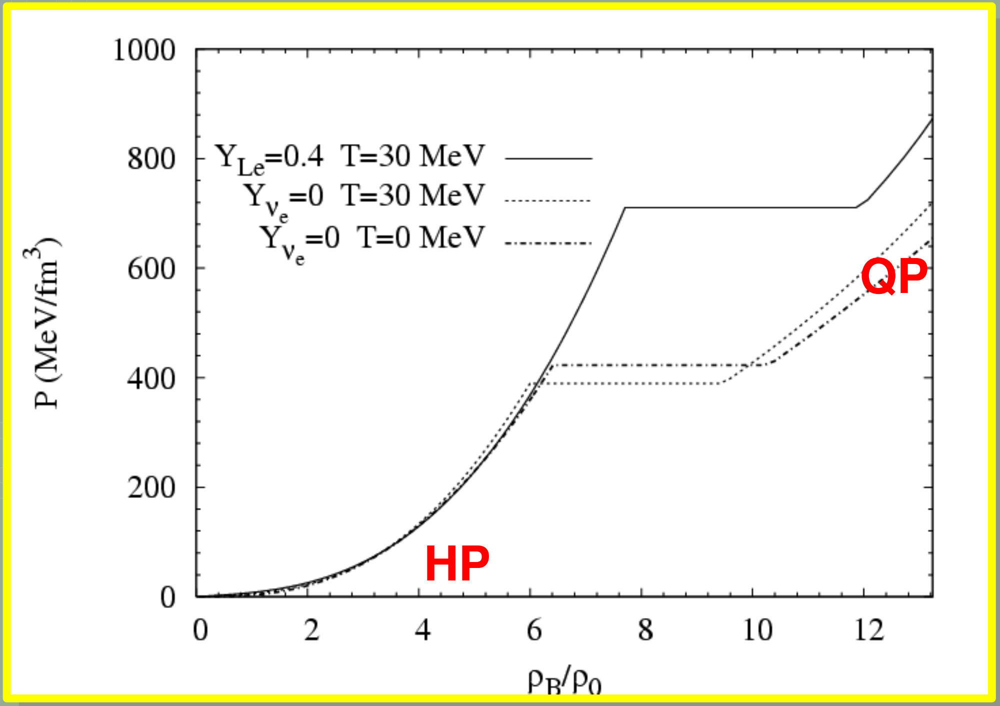
- The phase transition occurs IF no hyperons are present
- Neutrino trapping shifts the transition density at higher values

# MIT



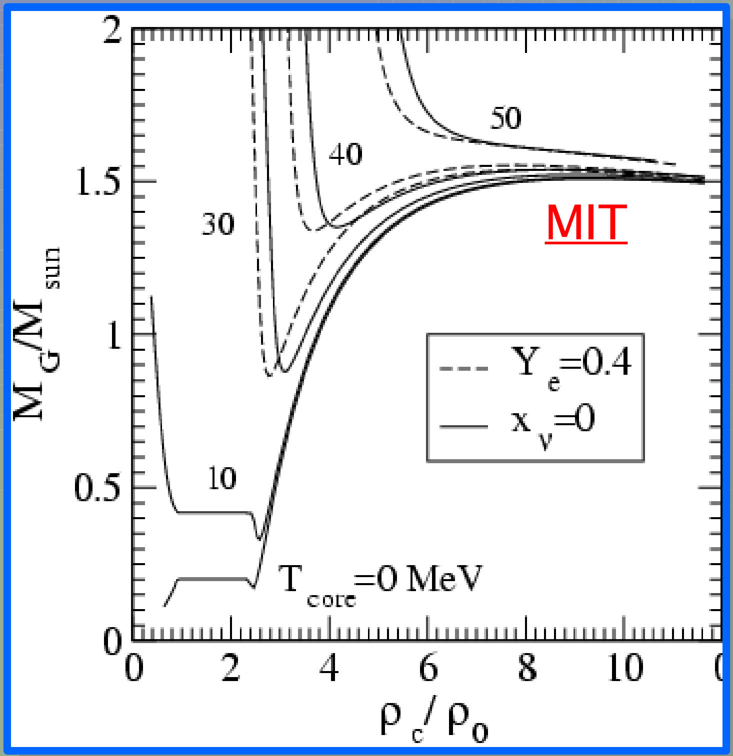

• No dependence on the neutrino fraction in the QP
• QP starts earlier in neutrino trapped matter

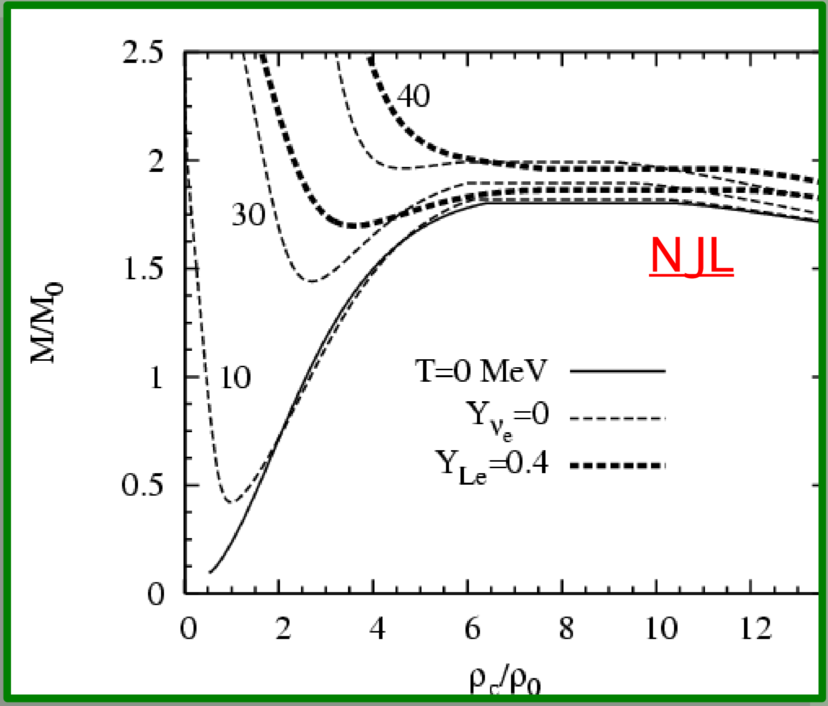
# NJL




• Strong dependence on the neutrino fraction in the QP
• QP starts later in neutrino trapped matter

# Hybrid PNS




- Maximum mass ~ 1.5 $M_{sun}$
- Heavy PNS : pure quark stars
  + thin layer of baryonic matter
  + outer envelope of hot matter

- Maximum mass ~ 1.8-1.9 $M_{su}$
- Instability of the pure QP :
  pure hadronic stars
  + a mixed hadron-quark core

Thermal + neutrino trapping effects more important for medium-low masses

# CONCLUSIONS

- ✓ BHF at finite T : EoS with nucleons, hyperons and neutrinos. Low values of the PNS with hyperons .

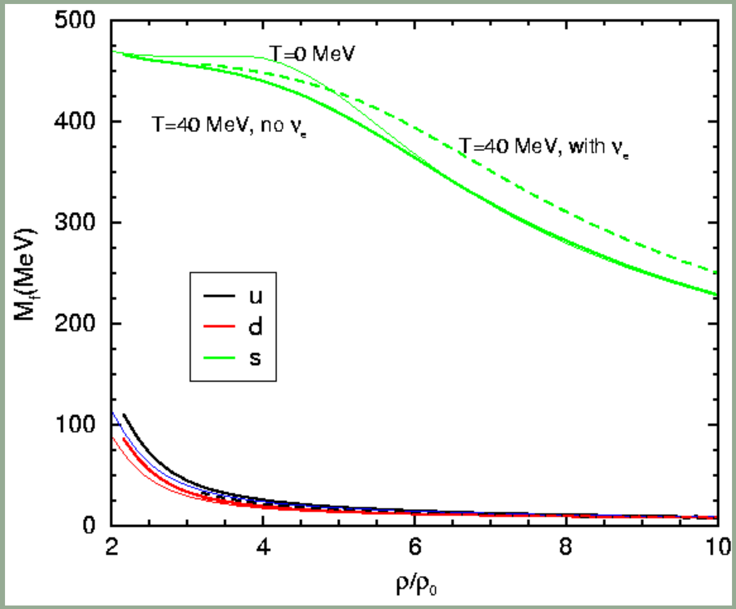
- ✓ Hybrid PNS : EoS dependent (independent) on the neutrino fraction in the NJL (MIT) model.
  Onset of phase transition at larger densities in NJL than in MIT.

- MIT PNS : The maximum mass of a hot PNS stabilizes around 1.5 solar masses. Stable pure quark phase.

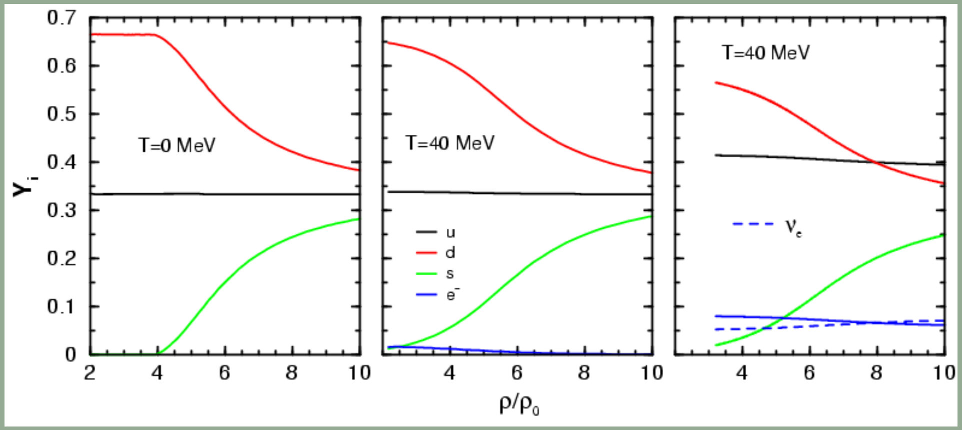
- NJL PNS : Maximum mass smaller than 2 solar masses. Unstable pure quark phase, at most a mixed phase.

# Effects of temperature and neutrino trapping in NJL

- Chiral symmetry restoration occurs first for (u,d) quarks, at higher density for the s-quark
- The mass of the s-quark starts to decrease only for $\rho / \rho_0 > 4$




- Weak thermal effects in neutrino free matter, except at low density
- Chiral symmetry restoration shifted to higher density in neutrino trapped matter
- Decrease of strangeness content



Scattering matrix

2B potential

FD distribution n(k)

$$\langle k_1 k_2 | K(W) | k_3 k_4 \rangle = \langle k_1 k_2 | V | k_3 k_4 \rangle + \mathrm{Re} \sum_{k_3' k_4'} \langle k_1 k_2 | V | k_{3'} k_{4'} \rangle \frac{\left[1 - n(k_3')\right]\left[1 - n(k_4')\right]}{W - E_{k_3'} - E_{k_4'} + i\varepsilon} \langle k_3' k_4' | K(W) | k_3 k_4 \rangle$$

Starting energy

$$U(k_1) = \sum_{k_2} n(k_2) \langle k_1 k_2 | K(W) | k_1 k_2 \rangle_A$$

S.p. potential

$$Fix\ \rho_i = \sum_k n_i(k)\ and\ T,\ then\ solve$$

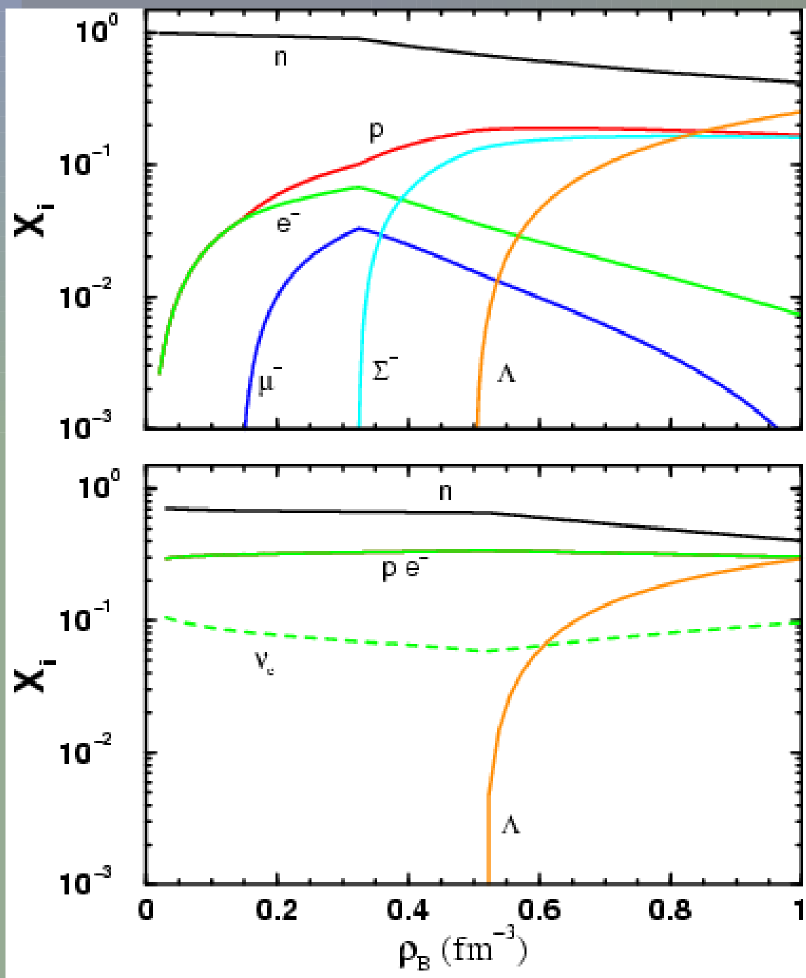
<u>*Frozen Correlations Approximation*</u>: U(k) independent of T

Simplified free energy $$f_i = \sum_k n_i(k) \left( \frac{k^2}{2m_i} + \frac{1}{2} U_i(k) \right) - T s_i$$

$$s_i = -\sum_k \left( n_i(k) \ln n_i(k) + [1 - n_i(k)] \ln[1 - n_i(k)] \right)$$

Pressure → $$P(\rho) = \rho^2 \frac{\partial (f/\rho)}{\partial \rho}$$

# Effects of the nucleon-hyperon interaction in beta-stable matter at T=0




## No ν trapping

- **Repulsive N interaction and onset shifted to larger ρ**
- **Slightly attractive NΛ potential Onset shifted to smaller ρ .**

## With ν trapping

- Disappearance of the .
- Unchanged Λ onset.

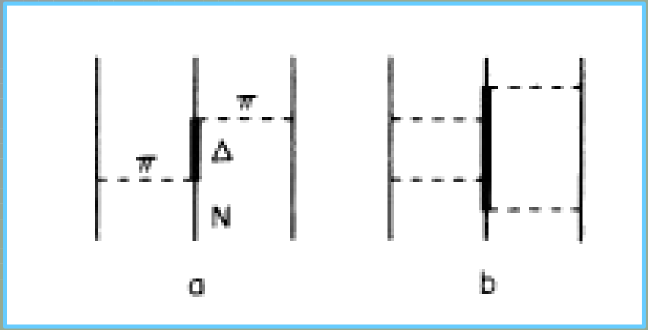
Role of the HH interaction ?

# Three-body forces(TBF) (No complete theory available yet !)

(Grange', Lejeune, Martzolff & Mathiot, PRC40, 1040 (1989))

Phenomenological
Urbana model

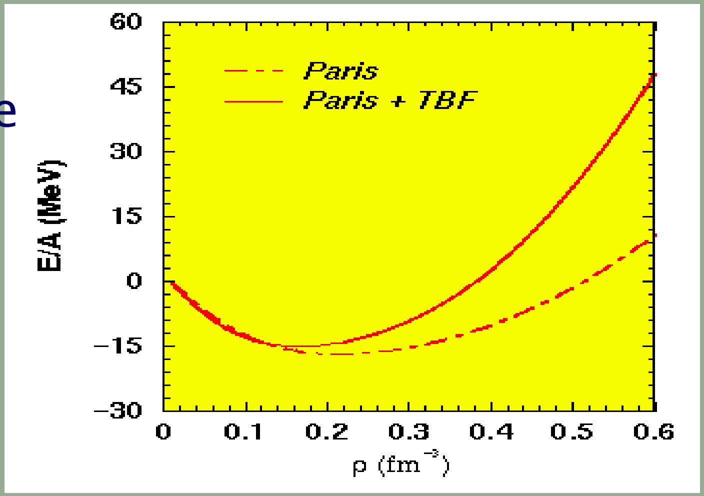
Carlson et al., NP A401,(1983) 59




(a) : Δ resonance (attractive)
(b) : Roper R resonance (repulsive)

TBF reduced to an effective two-body force by averaging over the position of the third particle :

- Correct saturation point
- Symmetry energy $S_v \approx 32$ MeV
- Incompressibility $K \approx 210$ MeV




M. Baldo et al., A&A 328, 274 (1997)