Isolated Neutron Stars : from the Interior to the Surface
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A Microscopic Equation of State for Protoneutron Stars

Fiorella Burgio

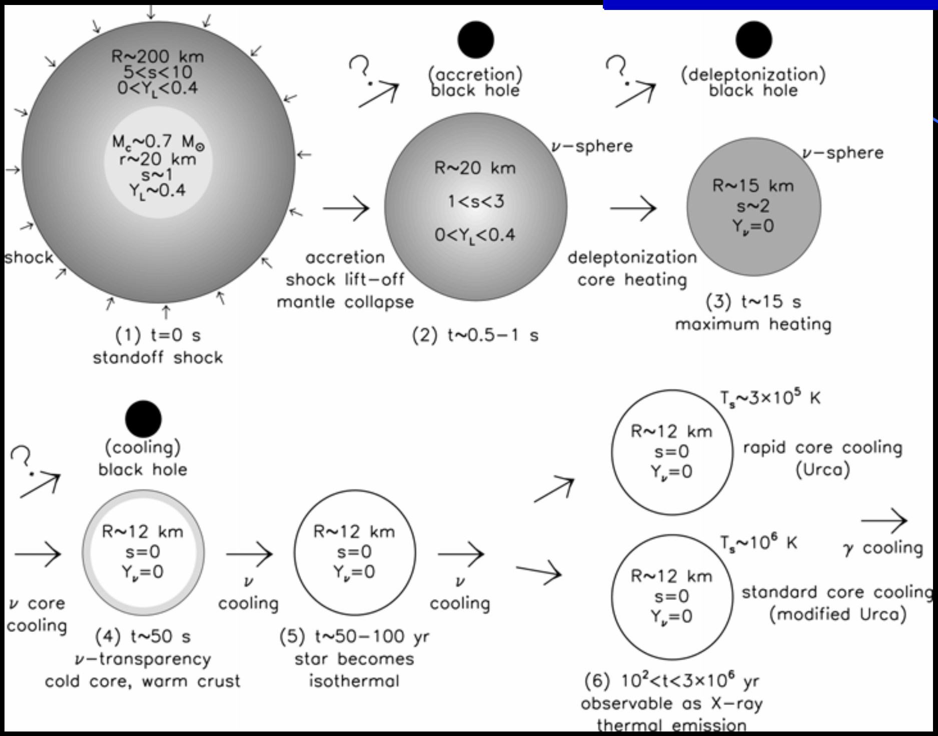
INFN Sezione di Catania, Italy
http://www.ct.ifn.it/~burgio

COLLABORATION
O. Nicotra, M. Baldo, H.-J. Schulze (INFN Catania)

Outline

- Protoneutron Stars (PNS)
- Equation of State (EoS) of Nuclear Matter at finite temperature
- Stellar Matter Composition
- PNS Structure
- Conclusions

Protoneutron Stars



M. Prakash et al. (1997)

- t ~ 50 sec
- S ~ 1-2
- ν–trapping (1st stage)
- ν free (2nd stage)

New effects on stellar matter composition :

1. Thermal effects $T \cong 30 - 40$ MeV
2. Neutrino trapping $\mu_\nu \neq 0$

How β–equilibrium changes

$$n \to p + e^- + \bar{\nu}_e$$

$$e^- \to \mu^- + \nu_e + \bar{\nu}_\mu$$

Microscopic EoS
(main ingredients)

- **Finite Temperature BHF (Brueckner-Hartree-Fock)**
  1. Bloch-De Dominicis formulation
- **Realistic two-body interaction (Av18)**
  1. Argonne v18: modern parametrization of the N-N scattering phase shifts (Wiringa 1995).
- **Three Body Forces (TBF)**
  1. Nuclear matter saturation point improved
  2. Urbana interaction for nucleons only (Carlson 1983)
- **Thermodynamical quantities**
  1. Free energy, chemical potentials, pressure (Baldo & Ferreira, 1999)

BHF Equation of State at finite temperature

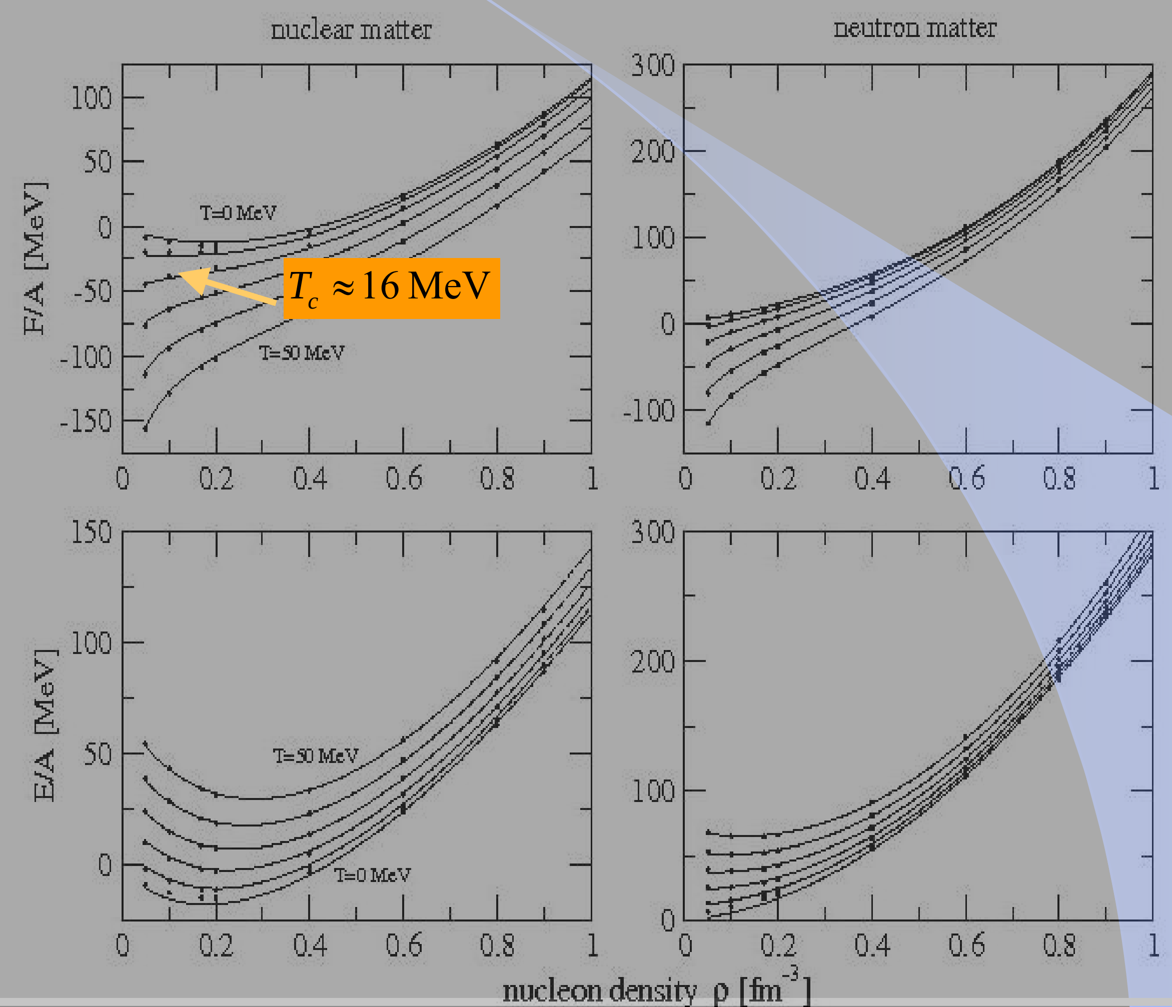
- Free energy

$$F = E - TS$$

- Chemical potentials for asymmetric NM

$$\mu_p(\rho, x_p) = \left[1 + \rho\frac{\partial}{\partial\rho} + (1 - x_p)\frac{\partial}{\partial x_p}\right]\frac{F}{A}$$

$$\mu_n(\rho, x_p) = \left[1 + \rho\frac{\partial}{\partial\rho} - x_p\frac{\partial}{\partial x_p}\right]\frac{F}{A}$$



➢ Stellar matter ($n,p,e^-,\mu^-,\Sigma,\Lambda$)

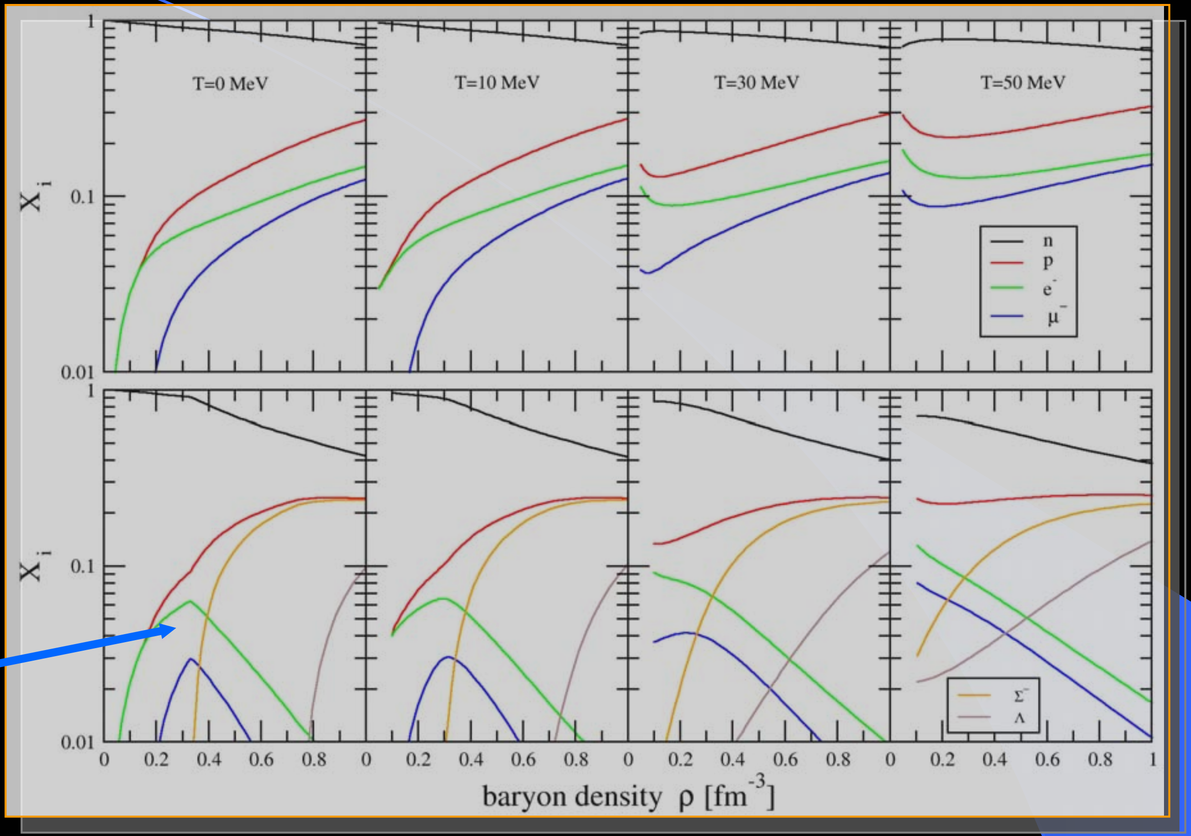
$$\mu_\nu = 0$$

- Composition :

$$\mu_i = b_i\mu_n - q_i(\mu_l - \mu_{\nu_l})$$
$$x_p = x_e + x_\mu + x_\Sigma$$
$$x_n + x_p + x_\Sigma + x_\Lambda = 1$$

(Lepton concentrations from a Fermi gas at finite T)

+ Free Hyperons



1. Strong T-dependence at low density because of tails in the Fermi distribution
2. Absence of production thresholds (muons, hyperons)
3. Increase of hyperon fractions at low density

O. Nicotra et al., astro-ph/0506066, A&A in press.

➢ Stellar matter (n,p,e^-,μ^-,Σ,Λ,ν's)

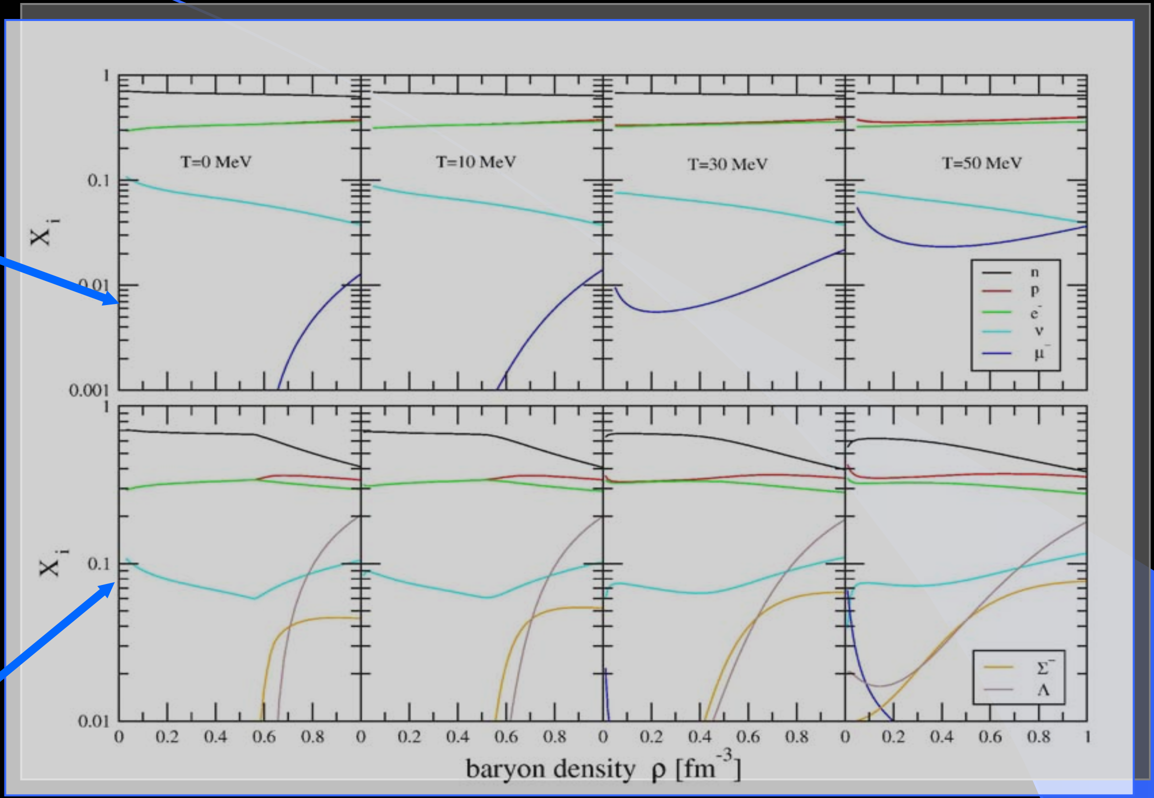
$\mu_\nu \neq 0$

- Composition

Nucleons only

$$x_{\nu_e} + x_e = 0.4$$
$$x_\mu + x_{\nu_\mu} = 0$$

+ Free Hyperons



1. Electron fraction larger in neutrino-trapped matter
2. Increase of proton population (more symmetric matter)
3. Onset of muons shifted at larger density
4. Onset of Σ (Λ) shifted to higher (lower) density
5. Hyperon fraction lower in neutrino-trapped matter

Effects of the NH and HH interaction ?

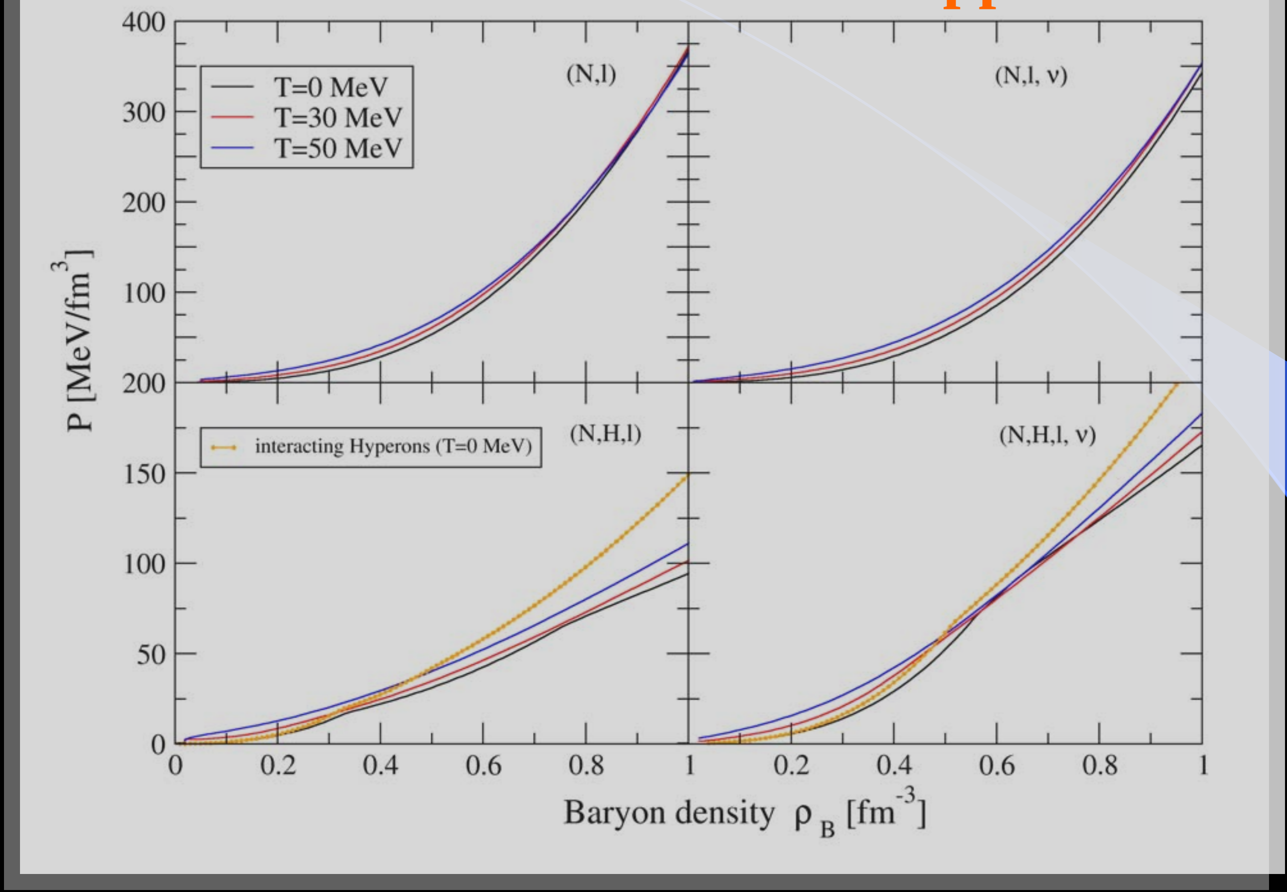
Equation of state

Pressure:

$$P = P_B + P_l$$

$$P_B = \rho^2 \frac{\partial(F/A)}{\partial \rho}$$

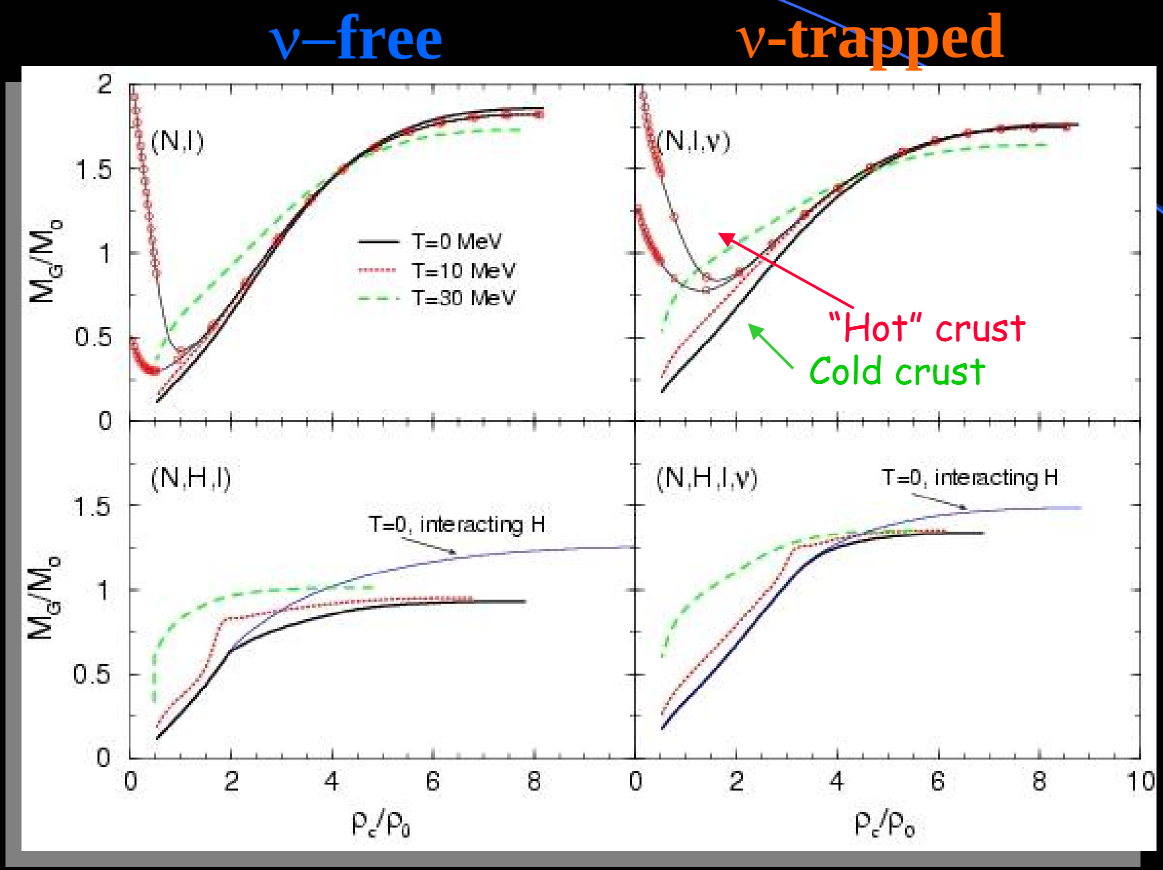
ν–free   ν-trapped



1. EOS stiffens slightly due to thermal effects (not at high density)
2. Strong EOS softening due to hyperons (slightly less with interaction)

1. Softening of the EOS if only N are present
2. Further softening due to hyperons , but less than in the neutrino-free case, due to their smaller concentration.

Stellar structure



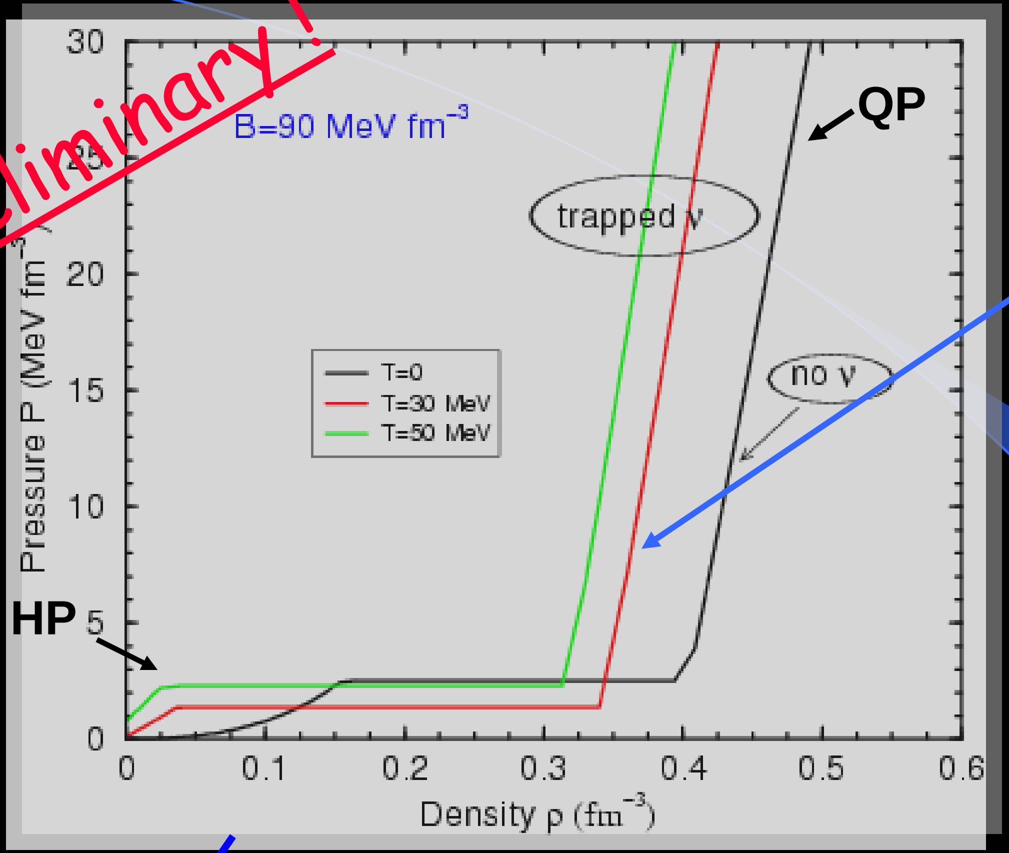
Reduction of the maximum mass due to thermal effects + neutrino trapping

Strong decrease of the maximum mass, down to about 1.3 Mo for NS and 1.5 Mo for PNS

1. The maximum mass for hyperonic cold stars is lower than 1.44 Mo, therefore unrealistic. Inclusion of the phase transition to quark matter.

2. The maximum mass of hyperonic protostars is larger than the one of cold neutron stars. Minor importance of hyperons in neutrino-trapped matter.

MIT Bag Model



Maxwell construction from HP to QP

Effects on the maximum mass

Composition	T (MeV)	M/M_o	ρ_c/ρ_o
(H,Q)	0	1.5	9.3
(H,Q,ν)	30 50	1.53 1.53	8.2 7.9

Conclusions

Nucleonic PNS

1. Thermal effects and neutrino trapping systematically reduce the maximum mass with increasing T.

Hyperonic PNS

1. The maximum mass is substantially larger than the one of the cold star, because both thermal effects and neutrino trapping tend to stiffen the EoS.
2. The addition of hyperons demands for the inclusion of quarks.