Title: Relativistic EOS for Supernovae Simulations

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Abstract: We construct the relativistic equation of state (EOS) of dense matter covering a wide range of temperature proton fraction and density for the use of core-collapse supernova simulations. The study is based on the relativistic mean-field (RMF) theory which can provide an excellent description of nuclear matter andfinite nuclei. The Thomas-Fermi approximation is adopted to describe the non-uniform matter which is composed of a lattice of heavy nuclei.We present two types of results. The first one takes into account only the nucleon degree of freedom while the second one considers additional contributions from Lambda hyperons. We tabulate the resulting EOS with an improved design of ranges and grids.

Contents

- Introduction
- Models used for EOS
- New version of EOS tables
- Λ hyperon effects
- Summary

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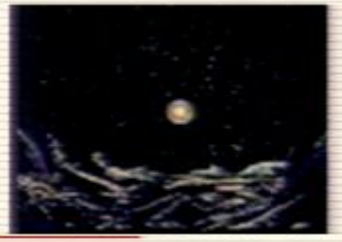

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- supernova explosion
- proton-neutron star cooling
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- ⋮

neutron star matter: charge neutrality; β equilibrium; $T \sim 0$

supernova matter: charge neutrality; fixed fractions; $T \neq 0$

what is the situation about EOS ?

For neutron stars, there are many EOS's, but...

For supernovae, there are only a few EOS's available

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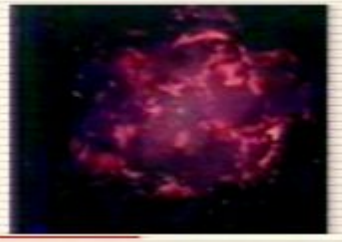

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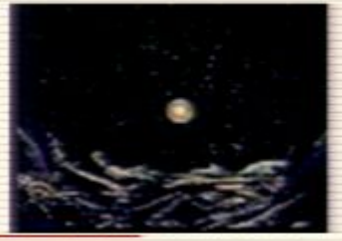

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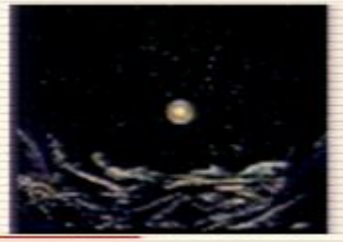

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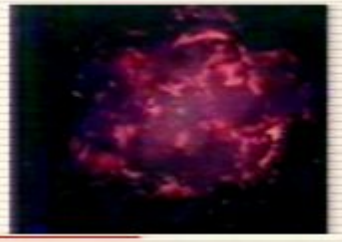

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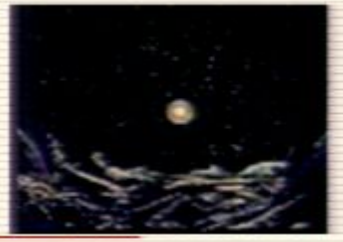

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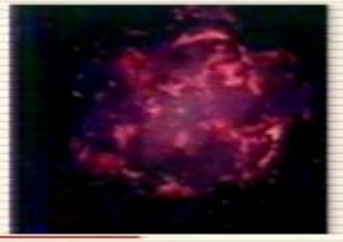

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EOS for supernovae

wide range

temperature (T):

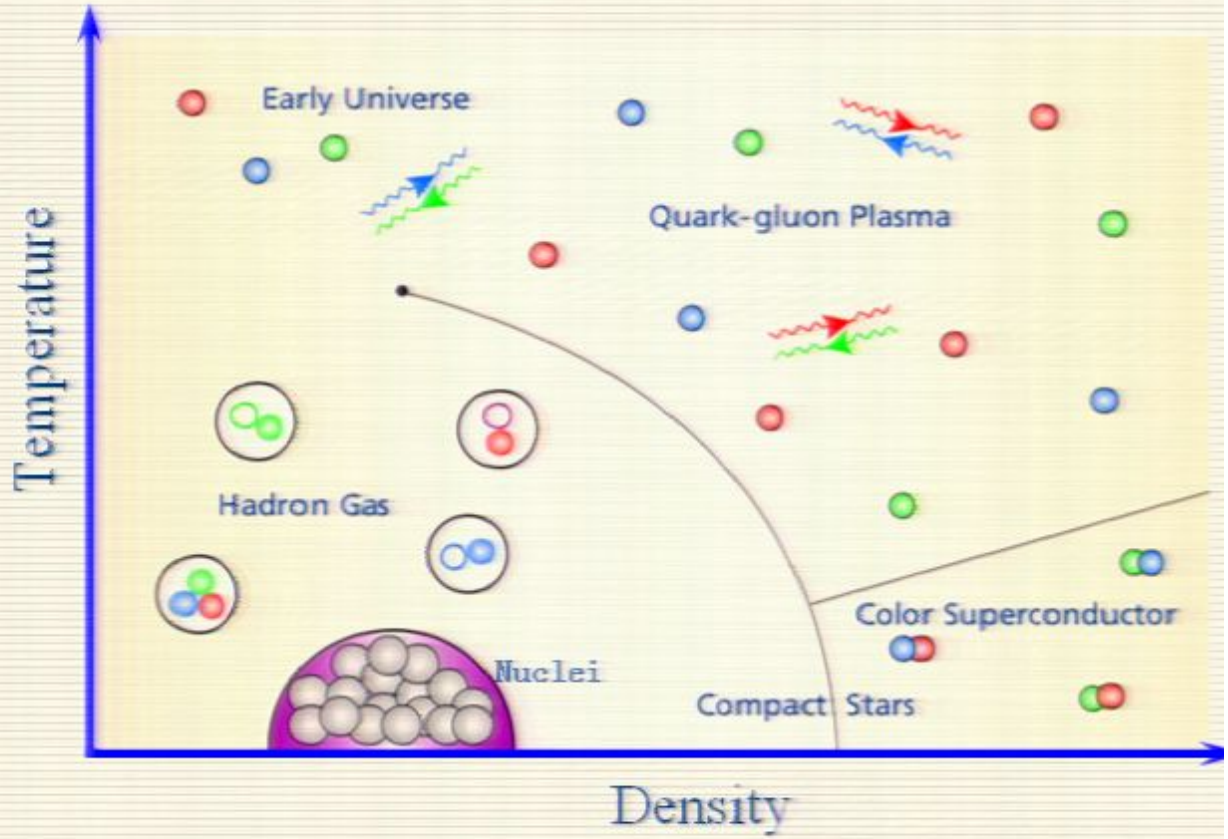
0 ~ 100 MeV

proton fraction (Yp):

0 ~ 0.6

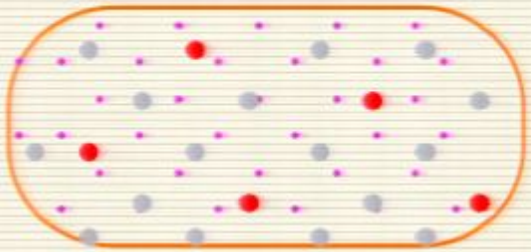
density (ρ_B):

10^5 ~ 10^{16} g/cm^3



Models used for EOS

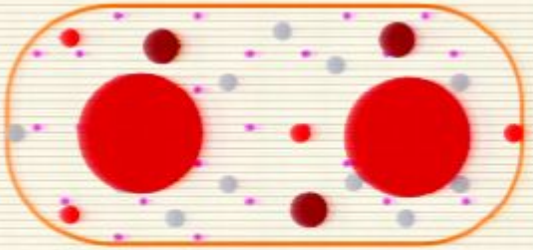
- uniform matter
  at high density



proton
neutron
electron

RMF (relativistic Mean Field)

- non-uniform matter
  at low density



nuclei
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RMF + Thomas-Fermi approximation

Models used for EOS

uniform matter

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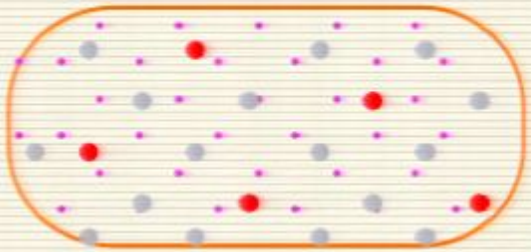

proton
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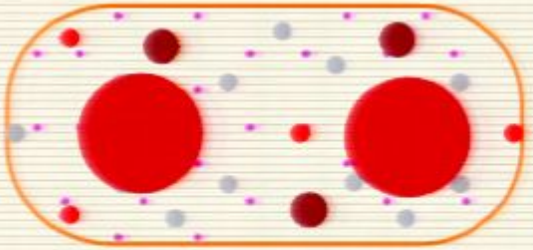
RMF (relativistic Mean Field)

non-uniform matter

at low density



nuclei
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proton
neutron
electron

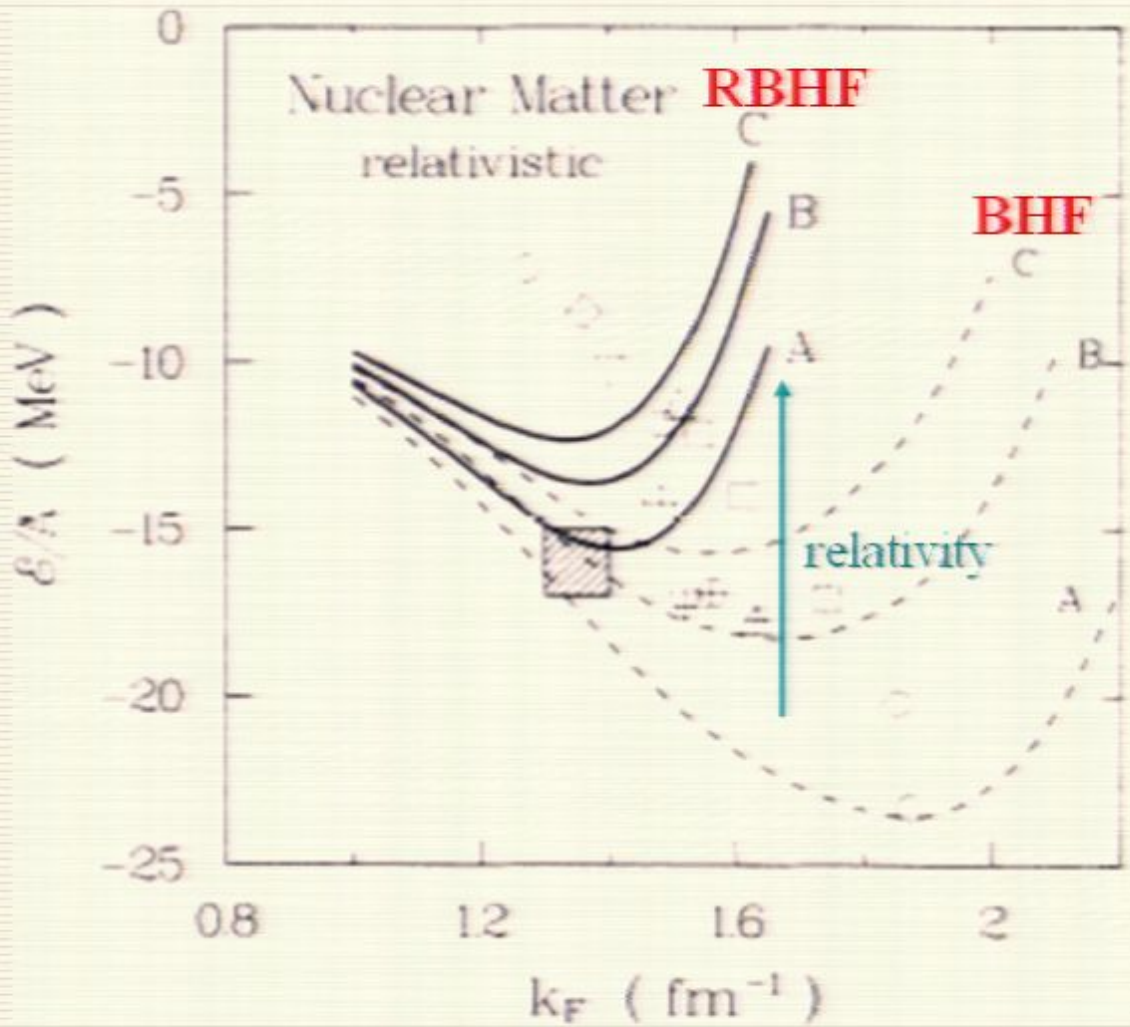
RMF + Thomas-Fermi approximation

Why prefer the RMF theory ?

nuclear many-body methods

nonrelativistic	relativistic
Shell Model	Relativistic Mean-Field (**RMF**)
Skyrme-Hartree-Fock (**SHF**)	Relativistic Hartree-Fock (**RHF**)
Brueckner-Hartree-Fock (**BHF**)	Relativistic Brueckner-Hartree-Fock (**RBHF**)
...	...

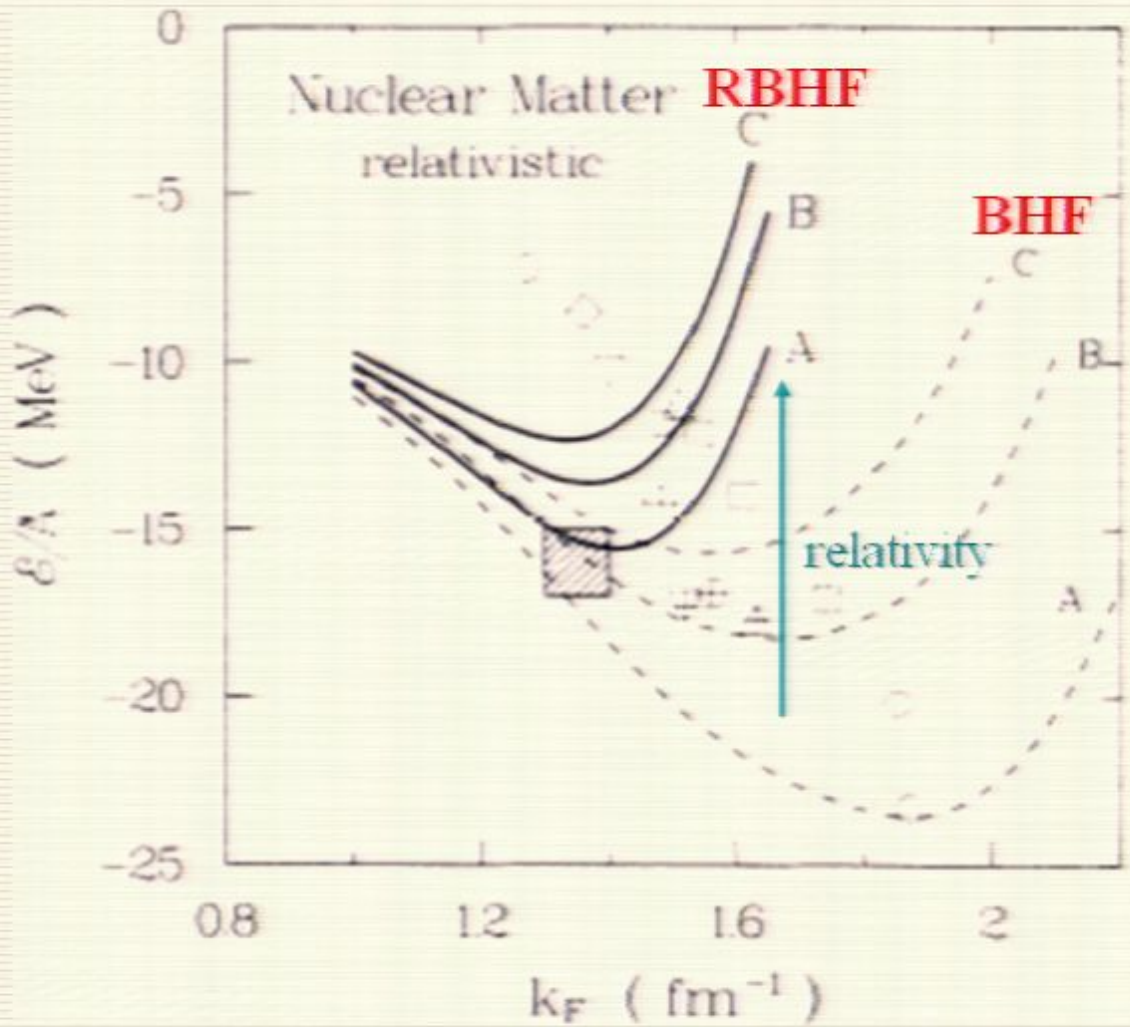
Relativity is important !



Brockmann, Machleidt, Phys. Rev. C 42 (1990) 1965

Relativity is important !

- natural explanation of spin-orbit force



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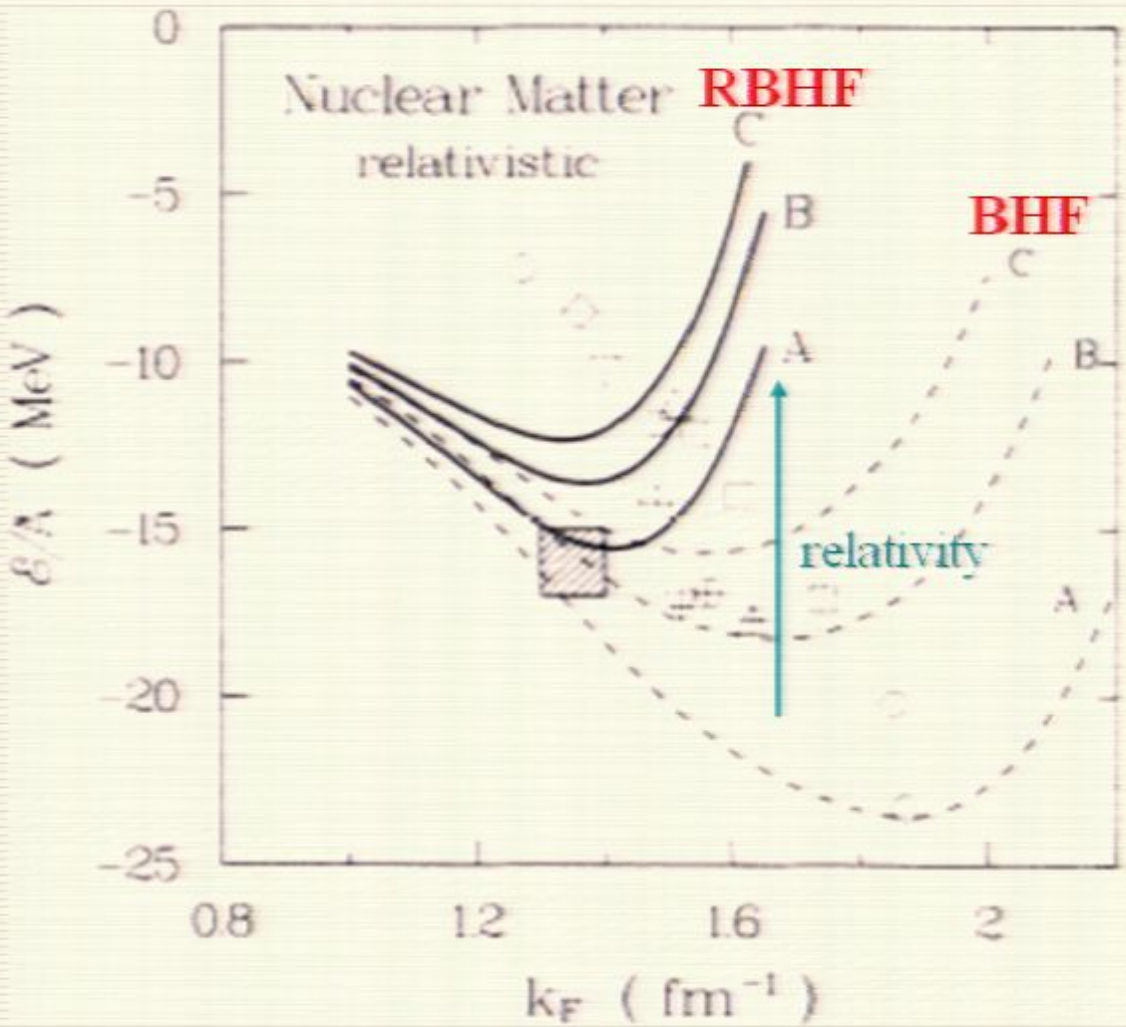
Relativity is important !

- natural explanation of spin-orbit force
- natural explanation of three-body force



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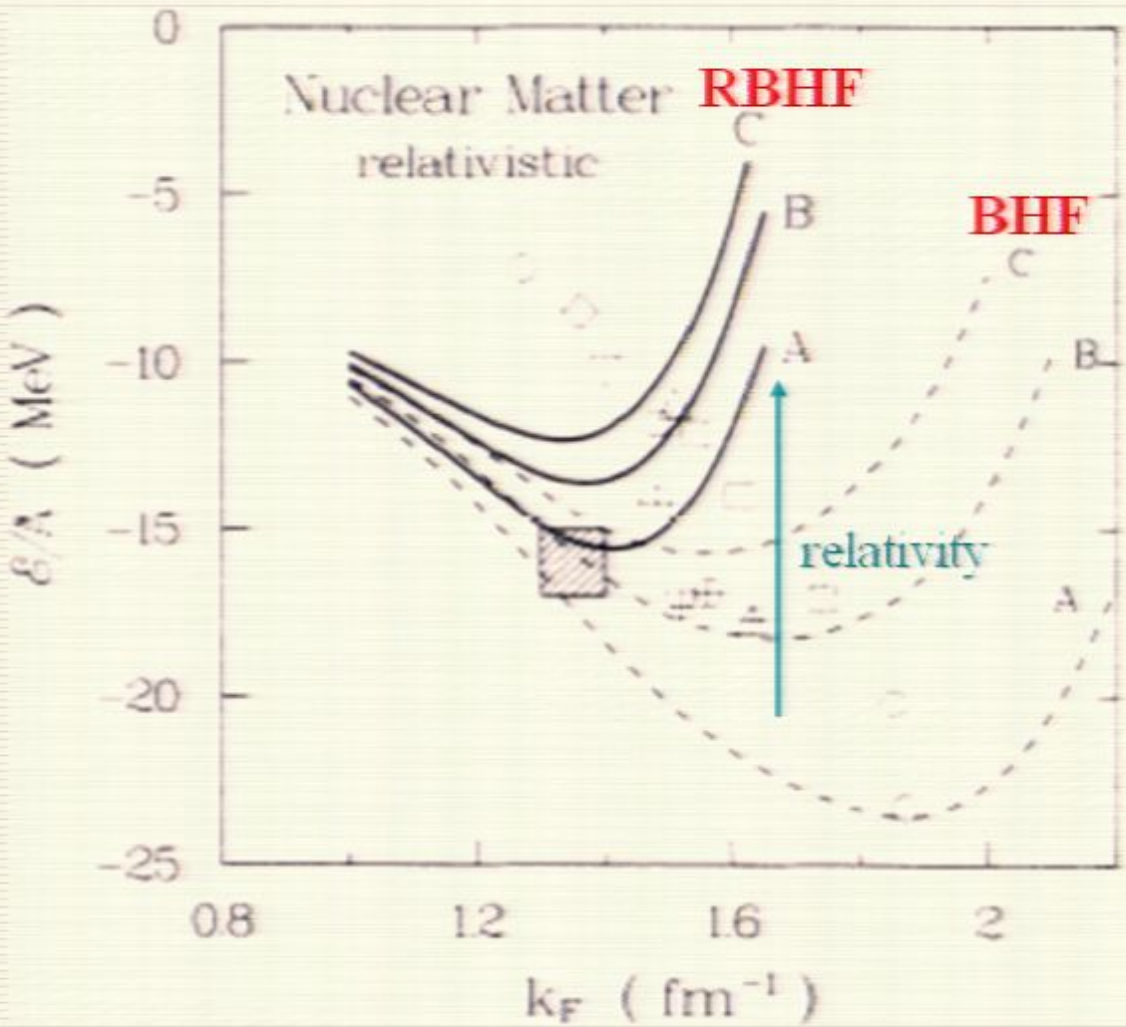
Relativity is important !

- natural explanation of spin-orbit force
- natural explanation of three-body force
- good saturation of nuclear matter



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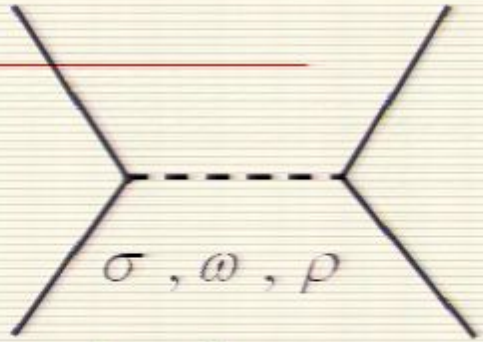
What is the RMF theory ?

Relativistic Mean Field Theory (RMF)



mean-field approximation: *meson field operators are replaced by their expectation values*

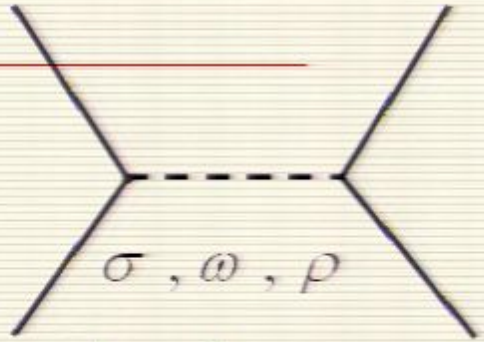
no-sea approximation: *contributions from the negative-energy Dirac sea are ignored*

Applications

	flavor SU(2)	flavor SU(3)
infinite matter:	*nuclear matter*	*strange hadronic matter*
finite system:	*nuclei*	*hypernuclei*

What is the RMF theory ?

Relativistic Mean Field Theory (RMF)



mean-field approximation: *meson field operators are replaced by their expectation values*

no-sea approximation: *contributions from the negative-energy Dirac sea are ignored*

Applications

	flavor SU(2)	flavor SU(3)
infinite matter:	*nuclear matter*	*strange hadronic matter*
finite system:	*nuclei*	*hypernuclei*

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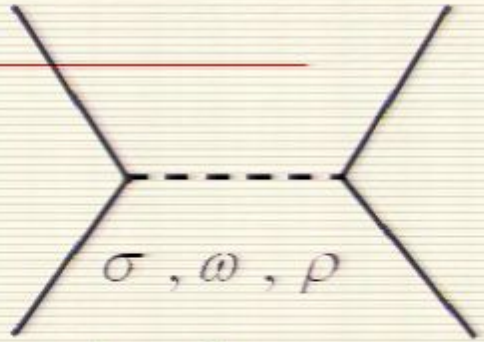

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Comparison with nuclear data

2157 nuclei

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(M^{i}_{\text{theo}} - M^{i}_{\text{expt}}\right)^{2}}{n}} = 2.1$$

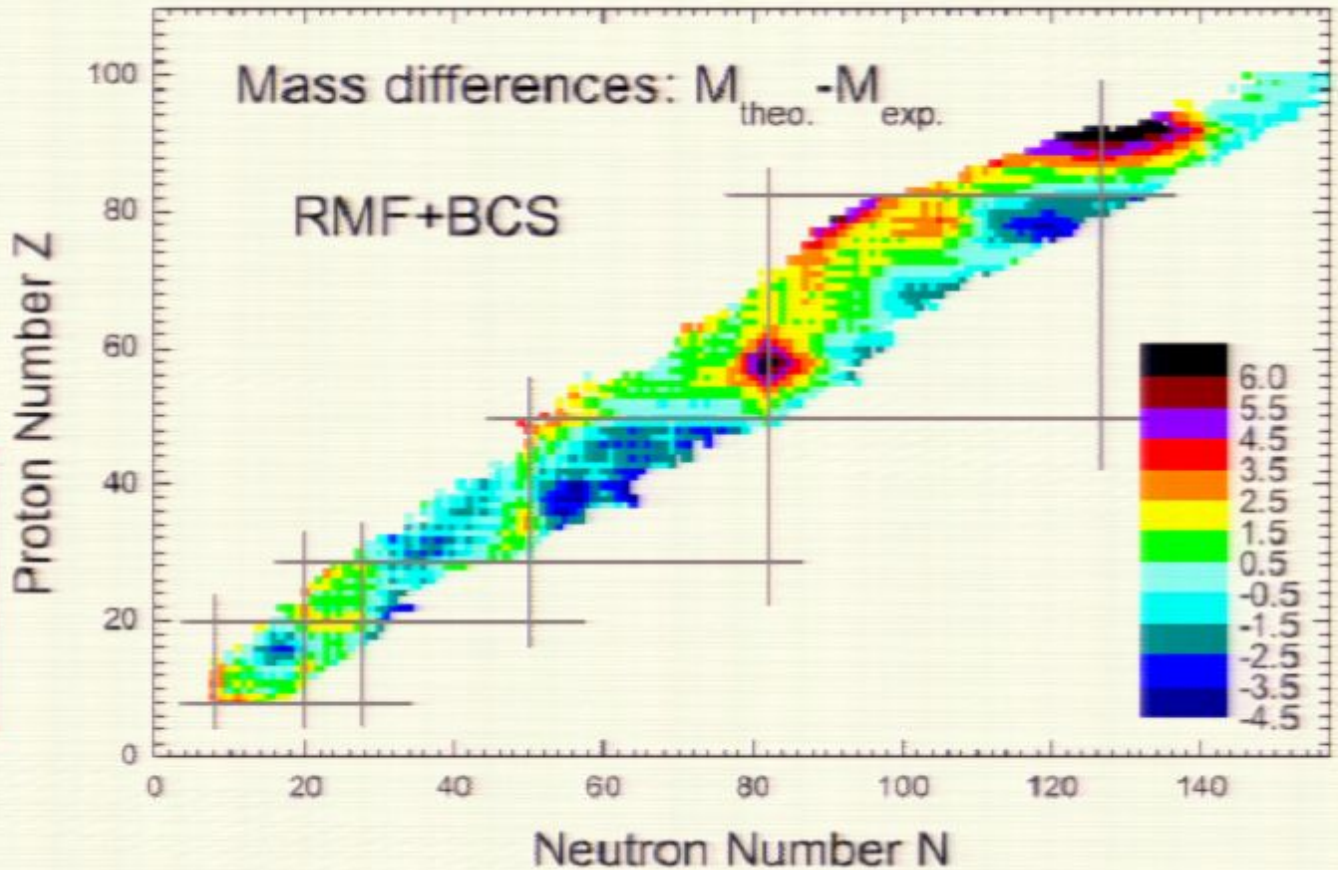

Fig. 2. Mass differences between the predictions of the present work and the experimental data for 2157 nuclei whose measured uncertainties for the masses are less than 0.2 MeV.[34)]

L.S.Geng, H.Toki, J.Meng, Prog. Theor. Phys. 113 (2005) 785

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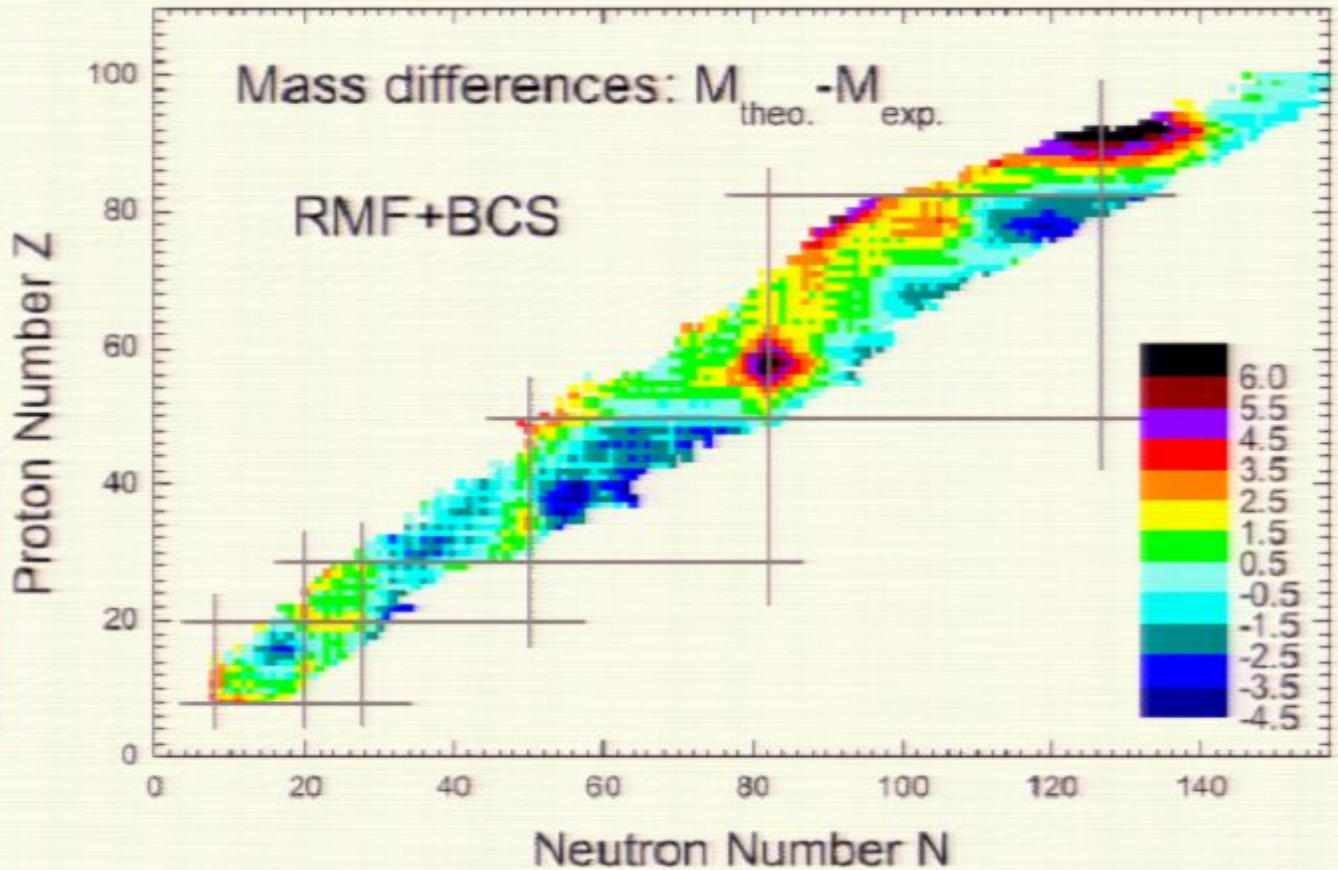

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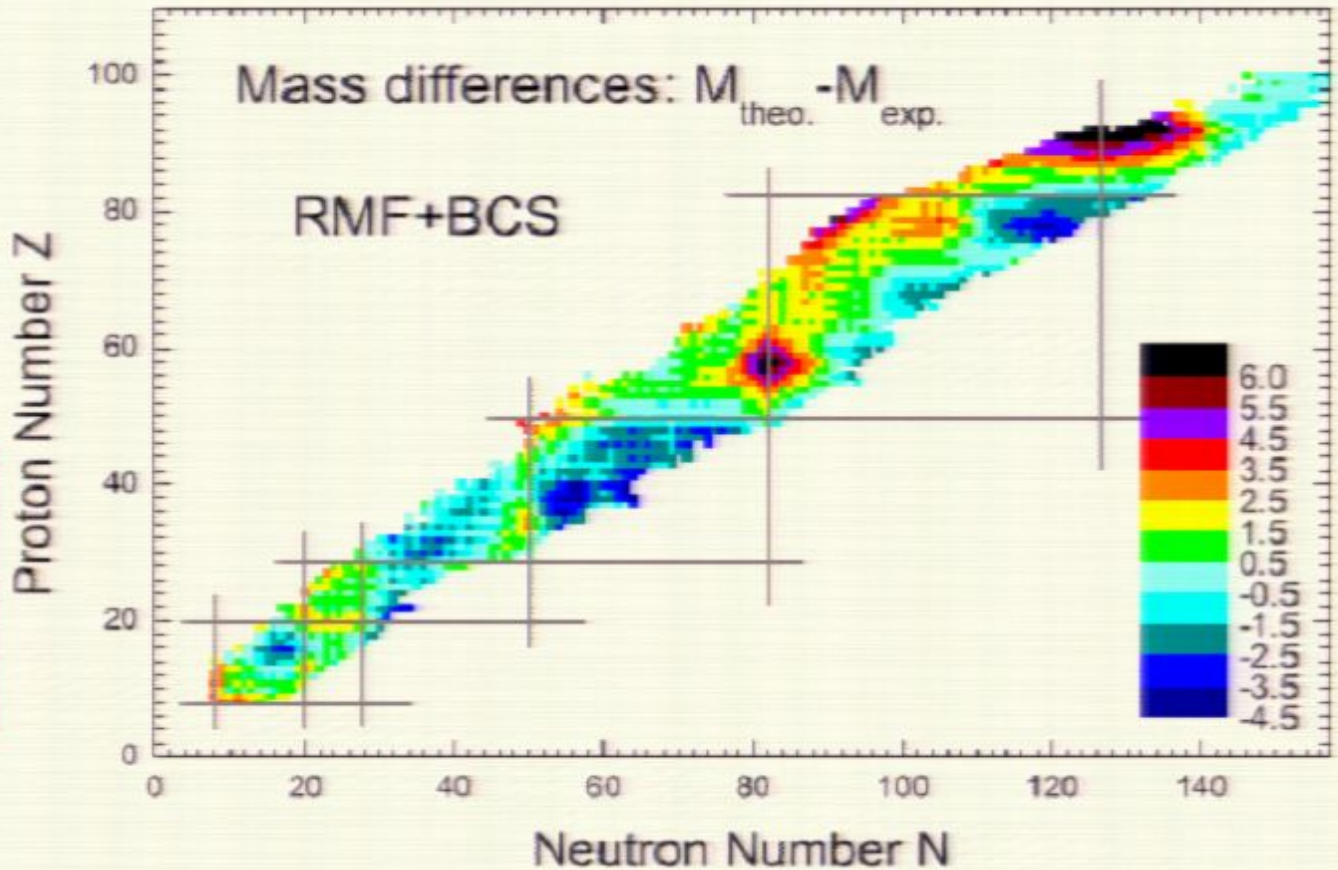

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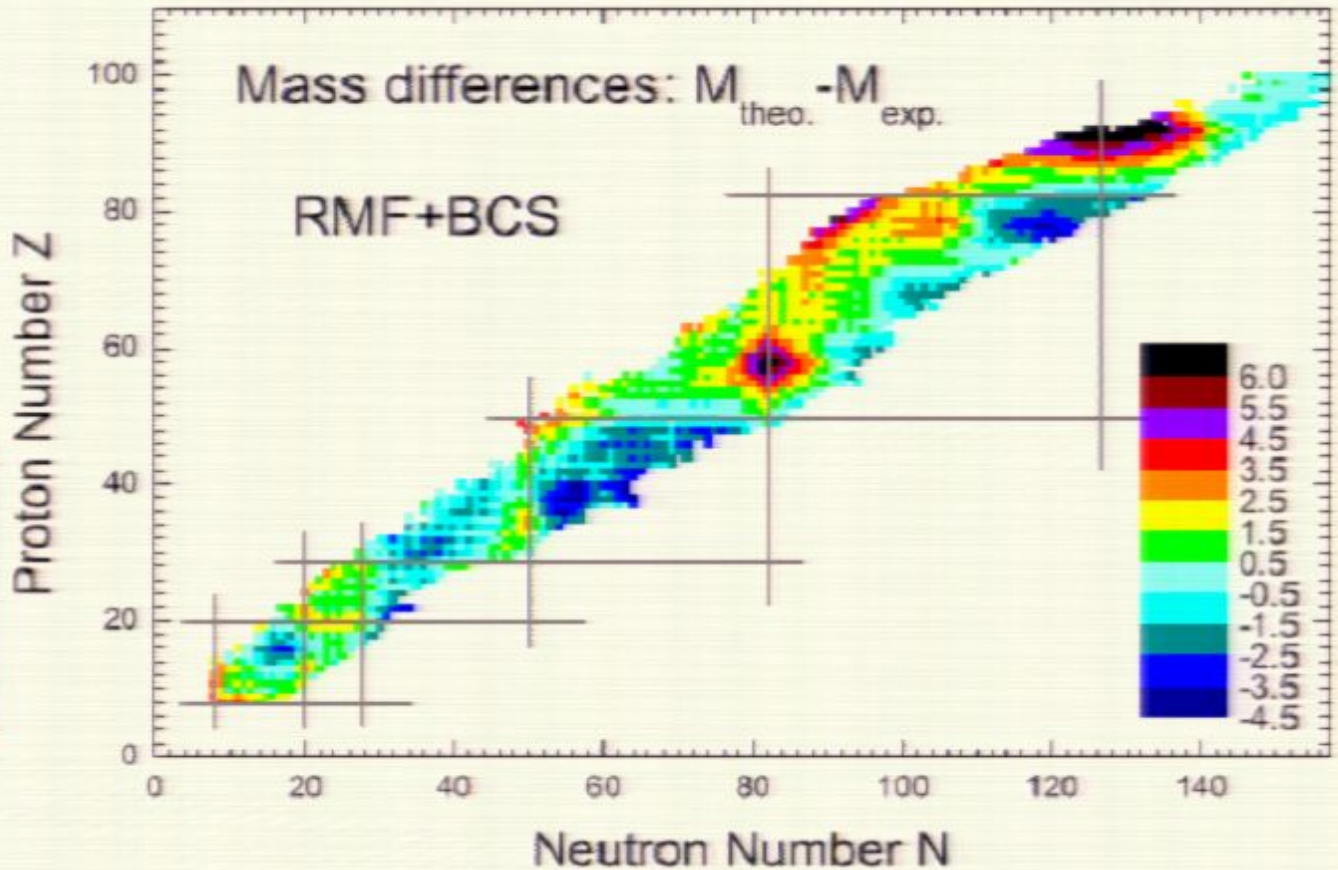

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Relativistic Mean Field Theory

Lagrangian

$$L = \overline{\psi}[i\gamma_\mu \partial^\mu - M - g_\sigma \sigma - g_\omega \gamma_\mu \omega^\mu - g_\rho \gamma_\mu \tau_a \rho^{a\mu}]\psi$$
$$+ \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4$$
$$- \frac{1}{4} W_{\mu\upsilon} W^{\mu\upsilon} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{4} c_3 (\omega_\mu \omega^\mu)^2$$
$$- \frac{1}{4} R^a_{\mu\upsilon} R^{a\mu\upsilon} + \frac{1}{2} m_\rho^2 \rho^a_\mu \rho^{a\mu}$$

TM1 parameter set

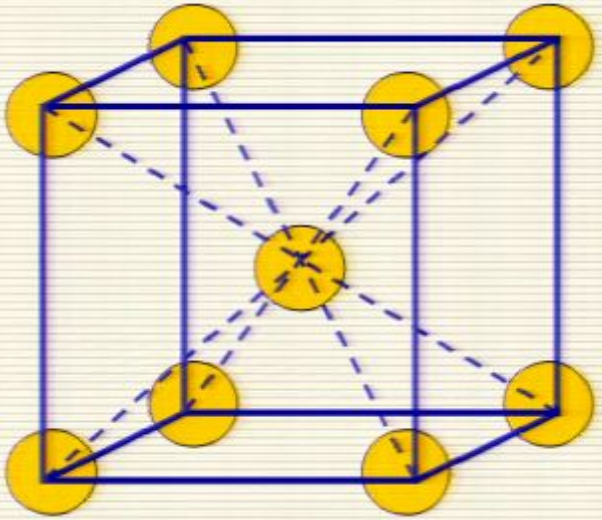
Lagrangian ⇒ Equations ⇒ Mean-Field Approximation

⇓

Calculate everything such as $\varepsilon, p, s \ldots$

Thomas-Fermi approximation

* body-centered cubic lattice
* parameterized nucleon distribution
* RMF input



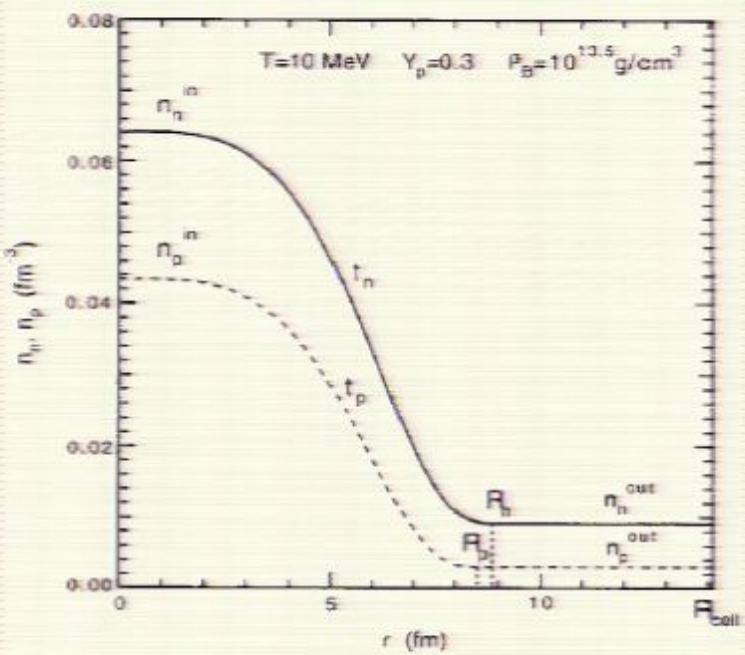
$$E = E_{bulk} + E_{surface} + E_{Coulomb} + E_{Lattice} + E_{electron}$$

assume states $\xrightarrow{\text{minimize free energy}}$ favorable state

Thomas-Fermi approximation

parameterized nucleon distribution

$$n_i(r) = \begin{cases} \left(n_i^{in} - n_i^{out}\right)\left[1 - \left(\frac{r}{R_i}\right)^{t_i}\right]^3 + n_i^{out}, & 0 \le r \le R_i \\ n_i^{out}, & R_i \le r \le R_{cell} \end{cases}$$



H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi, Nucl. Phys. A637 (1998) 435

Check the parameterization

Self-consistent Thomas-Fermi approximation

Lagrangian

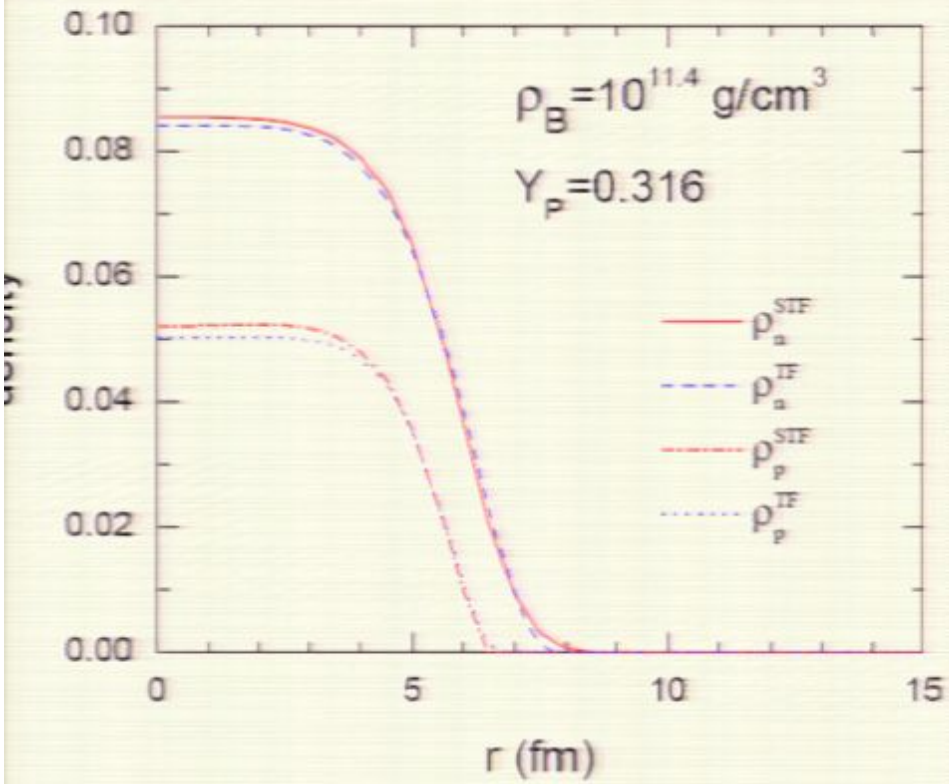
$$L_{RMF} = \bar{\Psi}\left[i\gamma_\mu \partial^\mu - (M + g_\sigma \sigma) - \left(g_\omega \omega + g_\rho \tau_3 \rho + e\frac{\tau_3 + 1}{2} A \right)\gamma^0 \right]\psi$$
$$- \frac{1}{2}(\nabla \sigma)^2 - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4$$
$$+ \frac{1}{2}(\nabla \omega)^2 + \frac{1}{2} m_\omega^2 \omega^2 + \frac{1}{4} c_3 \omega^4$$
$$+ \frac{1}{2}(\nabla \rho)^2 + \frac{1}{2} m_\rho^2 \rho^2 + \frac{1}{2}(\nabla A)^2$$
$$+ \sum_l \bar{\Psi}_l \left(i\gamma_\mu \partial^\mu - m_l + eA\gamma^0 \right)\psi_l$$

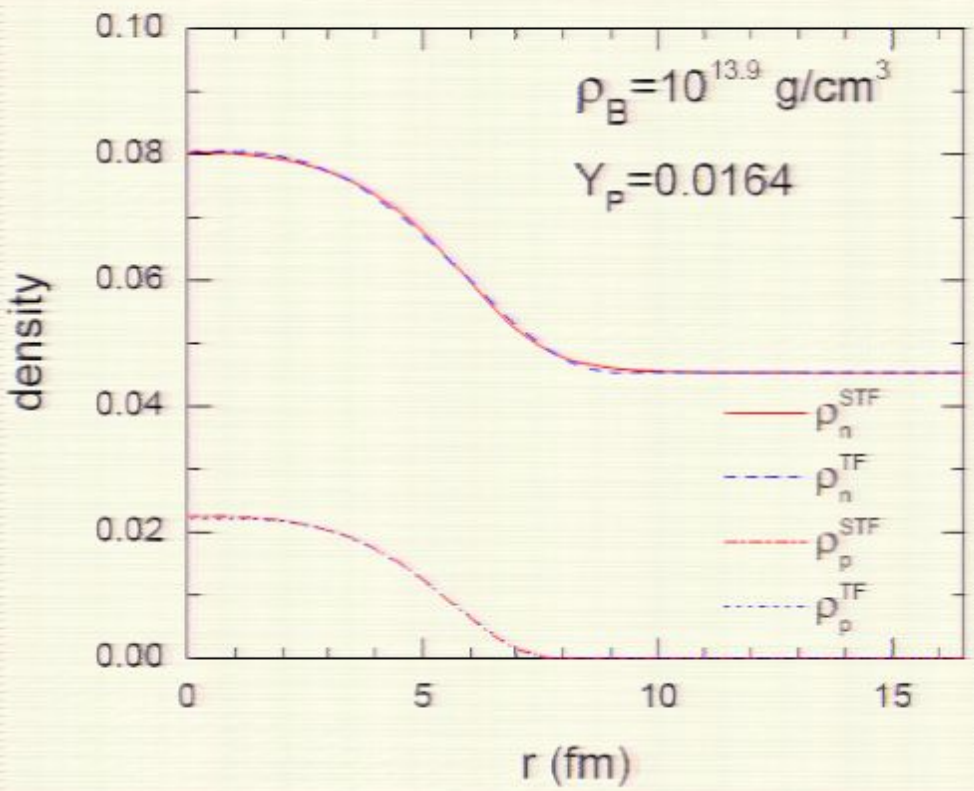
Equations

$$-\Delta\sigma + m_\sigma^2 \sigma = -g_\sigma \rho_s - g_2 \sigma^2 - g_3 \sigma^3,$$
$$-\Delta\omega + m_\omega^2 \omega = g_\omega \rho_v - c_3 \omega^3,$$
$$-\Delta\rho + m_\rho^2 \rho = g_\rho \left(\rho_v^p - \rho_v^n \right),$$
$$-\Delta A = e\left(\rho_v^p - \rho_v^l \right).$$

$$\left(k_F^b\right)^2 = \left(\mu_b - U_v^b\right)^2 - M^{*2}$$
$$M^* = M + g_\sigma \sigma$$
$$U_v^b = g_\omega \omega + g_\rho \tau_3 \rho + e\frac{\tau_3 + 1}{2} A$$

Self-consistent Thomas-Fermi approximation





New version of EOS tables

EOS1 (1998-version, nucleon)

Shen, Toki, Oyamatsu, Sumiyoshi, Prog. Theor. Phys. 100 (1998) 1013

EOS2 (2010-version, nucleon)

Shen, Toki, Oyamatsu, Sumiyoshi, arXiv:1105.1666 [astro-ph.HE]

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Home Page of Relativistic EOS table

Updated information is in readme

Documents

* readme.pdf
* guide_EOS1.pdf
* guide_EOS2.pdf
* guide_EOS3.pdf
* Prog. Theor. Phys. 100 (1998) 1013
* Nucl. Phys. A 637 (1998) 435

EOS table

	EOS1 1998-version nucleon	EOS2 2010-version nucleon	EOS3 2010-version nucleon + A
main table	eos1.tab.gz	eos2.tab.zip	eos3.tab.zip
table for T=0	eos1.t00.gz	eos2.t00.zip	eos3.t00.zip
table for Yp=0	eos1.yp0.gz	eos2.yp0.zip	eos3.yp0.zip

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E-mail: ssumi@numazu-ct.ac.jp

Comparison between EOS tables

		EOS1	EOS2	EOS3
Constituents	Uniform Matter	n, p, α	n, p, α	n, p, α, Λ
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T (MeV)	Range	$-1.0 \leq \log_{10}(T) \leq 2.0$	$-1.0 \leq \log_{10}(T) \leq 2.6$	$-1.0 \leq \log_{10}(T) \leq 2.6$
	Grid Spacing	$\Delta \log_{10}(T) \simeq 0.1$	$\Delta \log_{10}(T) = 0.04$	$\Delta \log_{10}(T) = 0.04$
	Points	32 (including $T = 0$)	92 (including $T = 0$)	92 (including $T = 0$)
Y_p	Range	$-2 \leq \log_{10}(Y_p) \leq -0.25$	$0 \leq Y_p \leq 0.65$	$0 \leq Y_p \leq 0.65$
	Grid Spacing	$\Delta \log_{10}(Y_p) = 0.025$	$\Delta Y_p = 0.01$	$\Delta Y_p = 0.01$
	Points	72 (including $Y_p = 0$)	66	66
ρ_B (g/cm^3)	Range	$5.1 \leq \log_{10}(\rho_B) \leq 15.4$	$5.1 \leq \log_{10}(\rho_B) \leq 16$	$5.1 \leq \log_{10}(\rho_B) \leq 16$
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ρ_B (g/cm^3)	Range	$5.1 \leq \log_{10}(\rho_B) \leq 15.4$	$5.1 \leq \log_{10}(\rho_B) \leq 16$	$5.1 \leq \log_{10}(\rho_B) \leq 16$
	Grid Spacing	$\Delta \log_{10}(\rho_B) \simeq 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$
	Points	104	110	110

- T number of points is increased; upper limit is extended; equal grid is used
- Y_p linear grid is used; upper limit is extended

Comparison between EOS tables

		EOS1	EOS2	EOS3
Constituents	Uniform Matter	n, p, α	n, p, α	n, p, α, Λ
	Non-uniform Matter	n, p, α, A	n, p, α, A	n, p, α, A
T (MeV)	Range	$-1.0 \leq \log_{10}(T) \leq 2.0$	$-1.0 \leq \log_{10}(T) \leq 2.6$	$-1.0 \leq \log_{10}(T) \leq 2.6$
	Grid Spacing	$\Delta \log_{10}(T) \simeq 0.1$	$\Delta \log_{10}(T) = 0.04$	$\Delta \log_{10}(T) = 0.04$
	Points	32 (including $T = 0$)	92 (including $T = 0$)	92 (including $T = 0$)
Y_p	Range	$-2 \leq \log_{10}(Y_p) \leq -0.25$	$0 \leq Y_p \leq 0.65$	$0 \leq Y_p \leq 0.65$
	Grid Spacing	$\Delta \log_{10}(Y_p) = 0.025$	$\Delta Y_p = 0.01$	$\Delta Y_p = 0.01$
	Points	72 (including $Y_p = 0$)	66	66
ρ_B (g/cm^3)	Range	$5.1 \leq \log_{10}(\rho_B) \leq 15.4$	$5.1 \leq \log_{10}(\rho_B) \leq 16$	$5.1 \leq \log_{10}(\rho_B) \leq 16$
	Grid Spacing	$\Delta \log_{10}(\rho_B) \simeq 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$
	Points	104	110	110

- T number of points is increased; upper limit is extended; equal grid is used
- Y_p linear grid is used; upper limit is extended

Comparison between EOS tables

		EOS1	EOS2	EOS3
Constituents	Uniform Matter	n, p, α	n, p, α	n, p, α, Λ
	Non-uniform Matter	n, p, α, A	n, p, α, A	n, p, α, A
T (MeV)	Range	$-1.0 \leq \log_{10}(T) \leq 2.0$	$-1.0 \leq \log_{10}(T) \leq 2.6$	$-1.0 \leq \log_{10}(T) \leq 2.6$
	Grid Spacing	$\Delta \log_{10}(T) \simeq 0.1$	$\Delta \log_{10}(T) = 0.04$	$\Delta \log_{10}(T) = 0.04$
	Points	32 (including $T = 0$)	92 (including $T = 0$)	92 (including $T = 0$)
Y_p	Range	$-2 \leq \log_{10}(Y_p) \leq -0.25$	$0 \leq Y_p \leq 0.65$	$0 \leq Y_p \leq 0.65$
	Grid Spacing	$\Delta \log_{10}(Y_p) = 0.025$	$\Delta Y_p = 0.01$	$\Delta Y_p = 0.01$
	Points	72 (including $Y_p = 0$)	66	66
ρ_B (g/cm^3)	Range	$5.1 \leq \log_{10}(\rho_B) \leq 15.4$	$5.1 \leq \log_{10}(\rho_B) \leq 16$	$5.1 \leq \log_{10}(\rho_B) \leq 16$
	Grid Spacing	$\Delta \log_{10}(\rho_B) \simeq 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$
	Points	104	110	110

- T number of points is increased; upper limit is extended; equal grid is used

Comparison between EOS tables

		EOS1	EOS2	EOS3
Constituents	Uniform Matter	n, p, α	n, p, α	n, p, α, Λ
	Non-uniform Matter	n, p, α, A	n, p, α, A	n, p, α, A
T (MeV)	Range	$-1.0 \leq \log_{10}(T) \leq 2.0$	$-1.0 \leq \log_{10}(T) \leq 2.6$	$-1.0 \leq \log_{10}(T) \leq 2.6$
	Grid Spacing	$\Delta \log_{10}(T) \simeq 0.1$	$\Delta \log_{10}(T) = 0.04$	$\Delta \log_{10}(T) = 0.04$
	Points	32 (including $T = 0$)	92 (including $T = 0$)	92 (including $T = 0$)
Y_p	Range	$-2 \leq \log_{10}(Y_p) \leq -0.25$	$0 \leq Y_p \leq 0.65$	$0 \leq Y_p \leq 0.65$
	Grid Spacing	$\Delta \log_{10}(Y_p) = 0.025$	$\Delta Y_p = 0.01$	$\Delta Y_p = 0.01$
	Points	72 (including $Y_p = 0$)	66	66
ρ_B (g/cm^3)	Range	$5.1 \leq \log_{10}(\rho_B) \leq 15.4$	$5.1 \leq \log_{10}(\rho_B) \leq 16$	$5.1 \leq \log_{10}(\rho_B) \leq 16$
	Grid Spacing	$\Delta \log_{10}(\rho_B) \simeq 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$
	Points	104	110	110

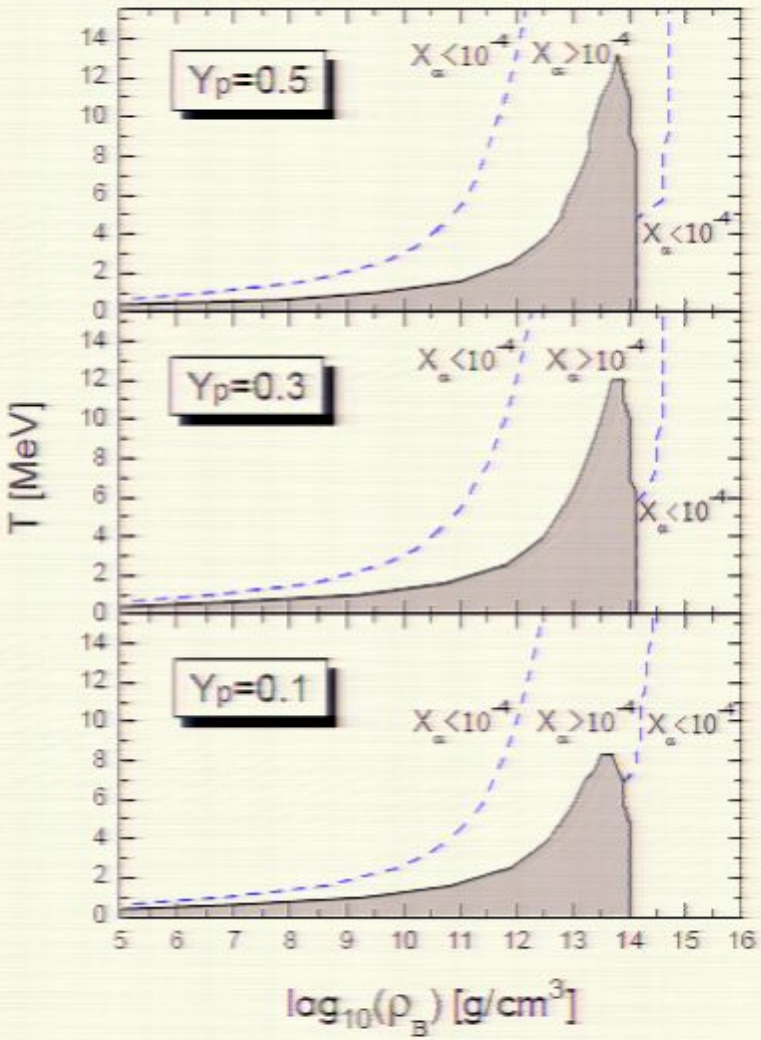
- T number of points is increased; upper limit is extended; equal grid is used
- Y_p linear grid is used; upper limit is extended

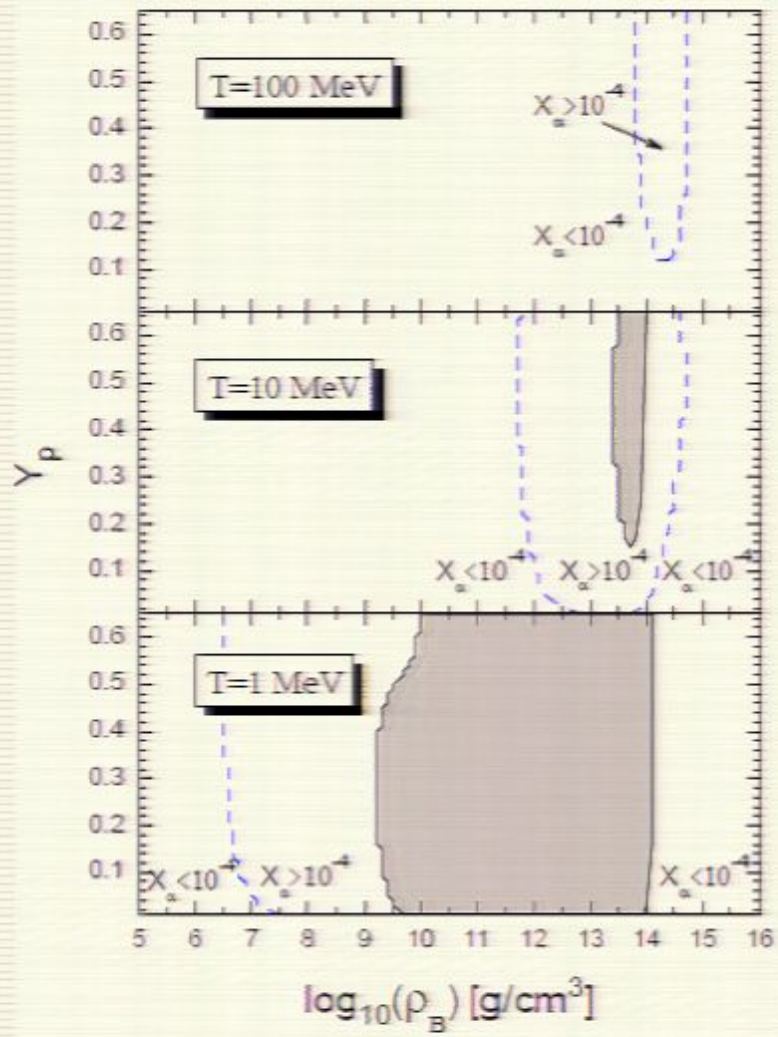
Comparison between EOS tables

		EOS1	EOS2	EOS3
Constituents	Uniform Matter	n, p, α	n, p, α	n, p, α, Λ
	Non-uniform Matter	n, p, α, A	n, p, α, A	n, p, α, A
T (MeV)	Range	$-1.0 \leq \log_{10}(T) \leq 2.0$	$-1.0 \leq \log_{10}(T) \leq 2.6$	$-1.0 \leq \log_{10}(T) \leq 2.6$
	Grid Spacing	$\Delta \log_{10}(T) \simeq 0.1$	$\Delta \log_{10}(T) = 0.04$	$\Delta \log_{10}(T) = 0.04$
	Points	32 (including $T = 0$)	92 (including $T = 0$)	92 (including $T = 0$)
Y_p	Range	$-2 \leq \log_{10}(Y_p) \leq -0.25$	$0 \leq Y_p \leq 0.65$	$0 \leq Y_p \leq 0.65$
	Grid Spacing	$\Delta \log_{10}(Y_p) = 0.025$	$\Delta Y_p = 0.01$	$\Delta Y_p = 0.01$
	Points	72 (including $Y_p = 0$)	66	66
ρ_B (g/cm^3)	Range	$5.1 \leq \log_{10}(\rho_B) \leq 15.4$	$5.1 \leq \log_{10}(\rho_B) \leq 16$	$5.1 \leq \log_{10}(\rho_B) \leq 16$
	Grid Spacing	$\Delta \log_{10}(\rho_B) \simeq 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$	$\Delta \log_{10}(\rho_B) = 0.1$
	Points	104	110	110

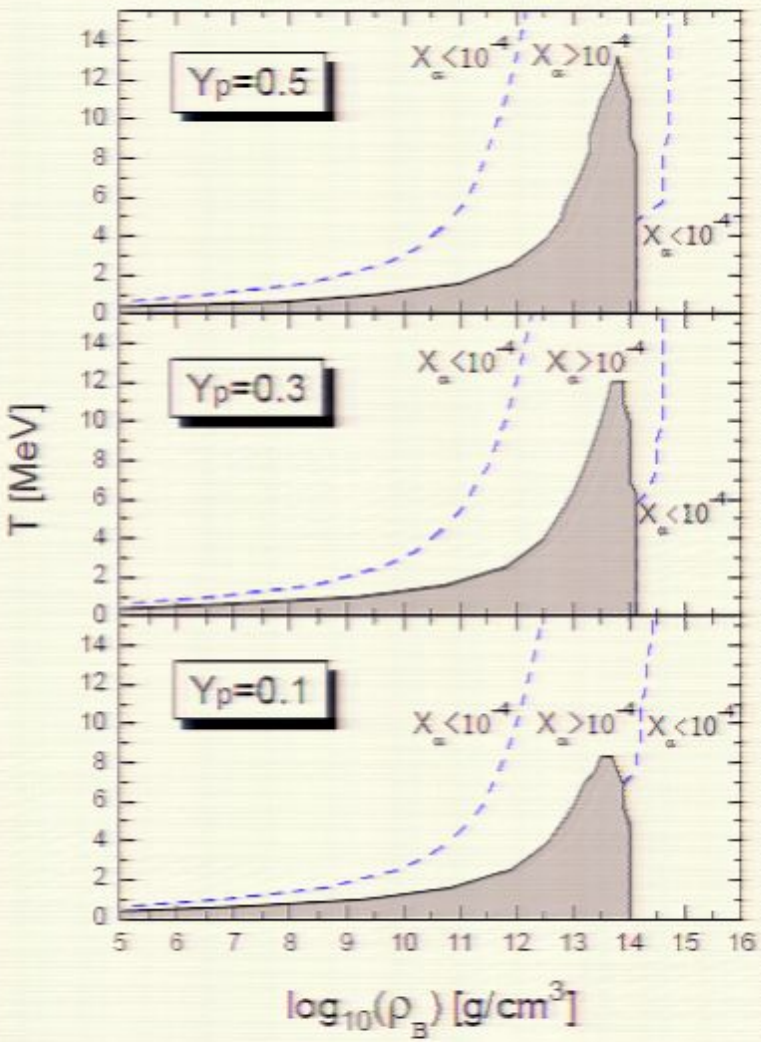
- T number of points is increased; upper limit is extended; equal grid is used
- Y_p linear grid is used; upper limit is extended
- ρ_B upper limit is extended; equal grid is used

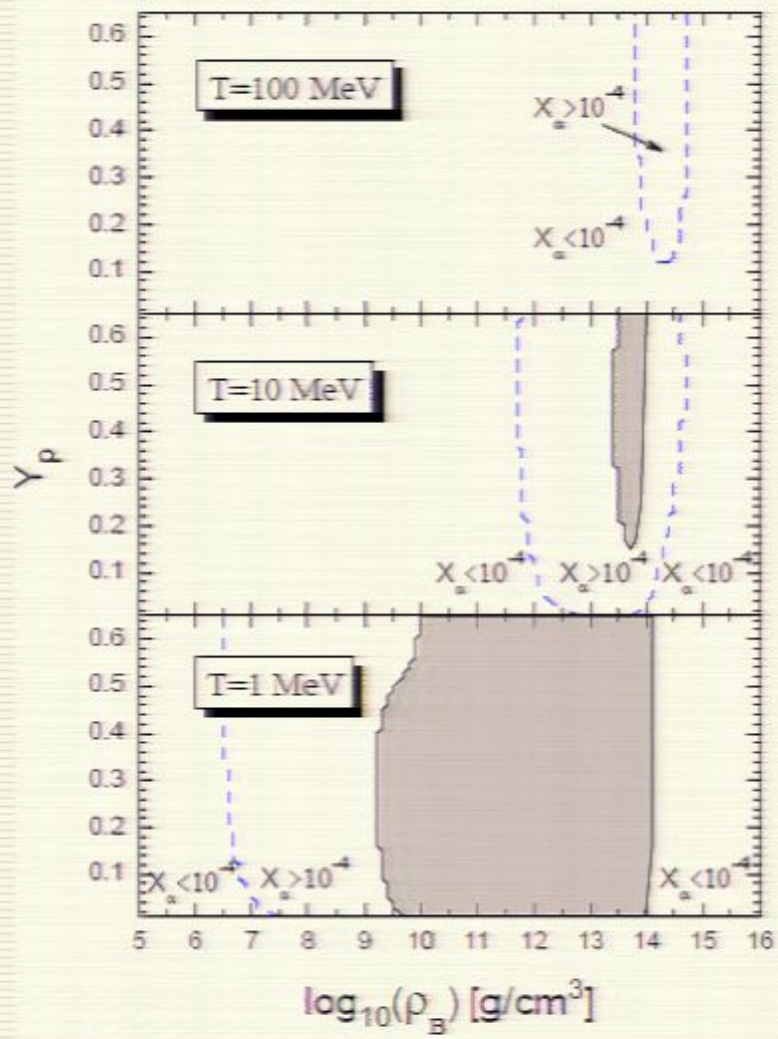
Phase diagrams



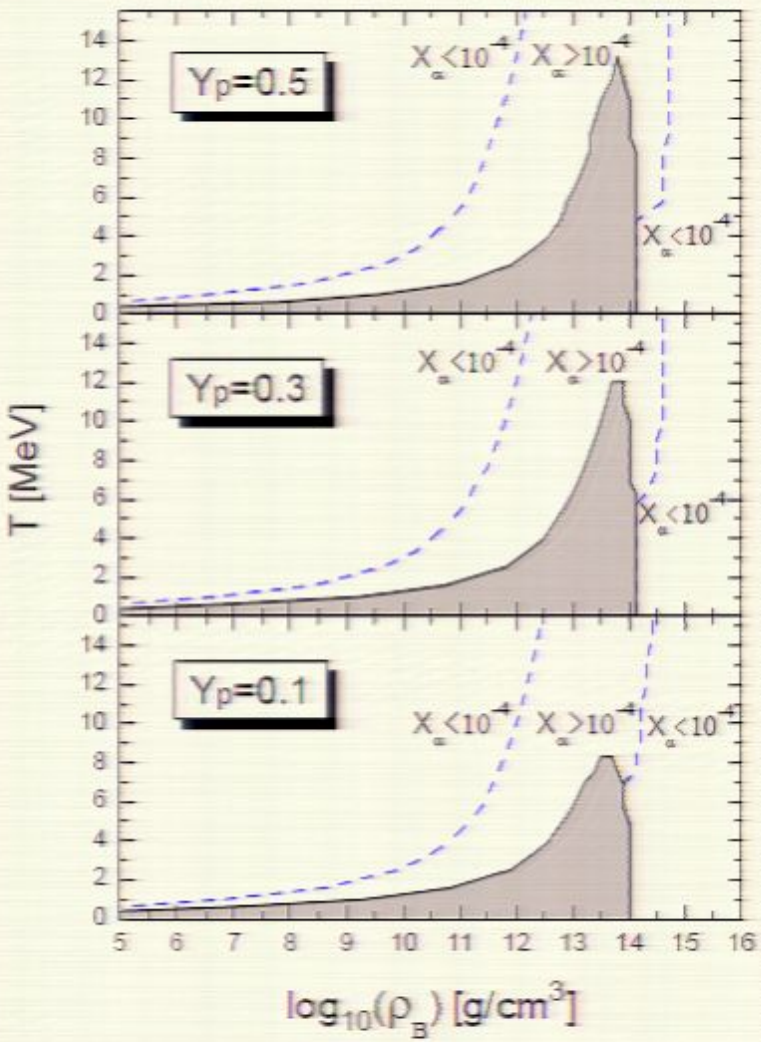


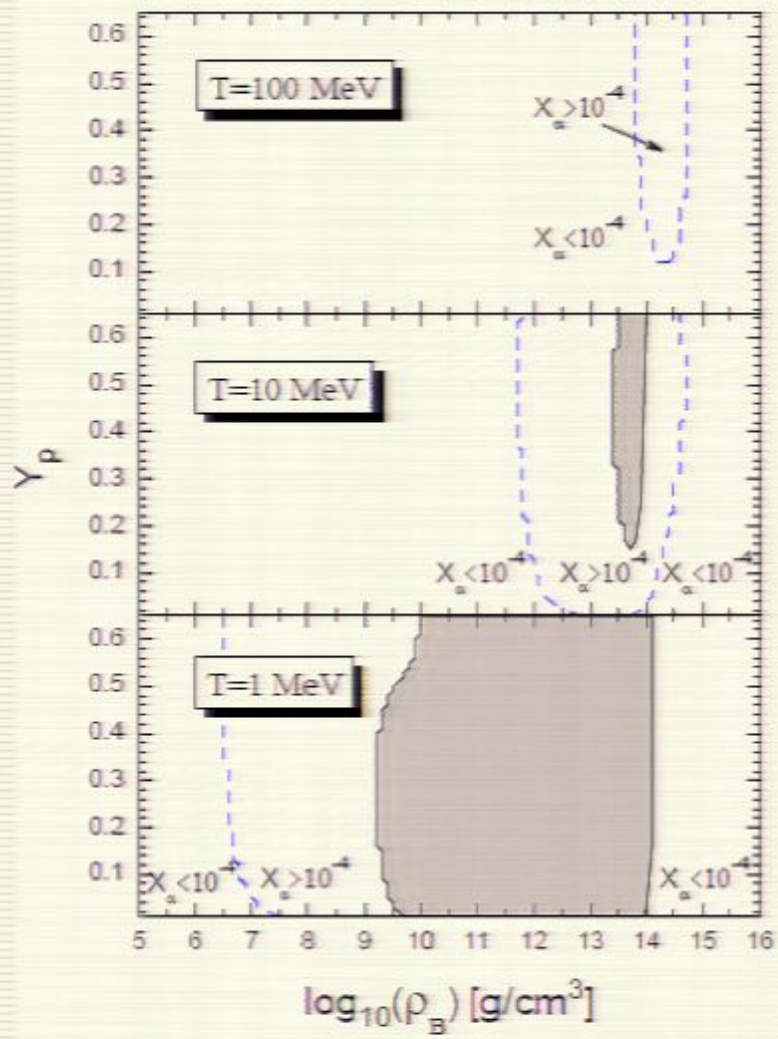
Phase diagrams



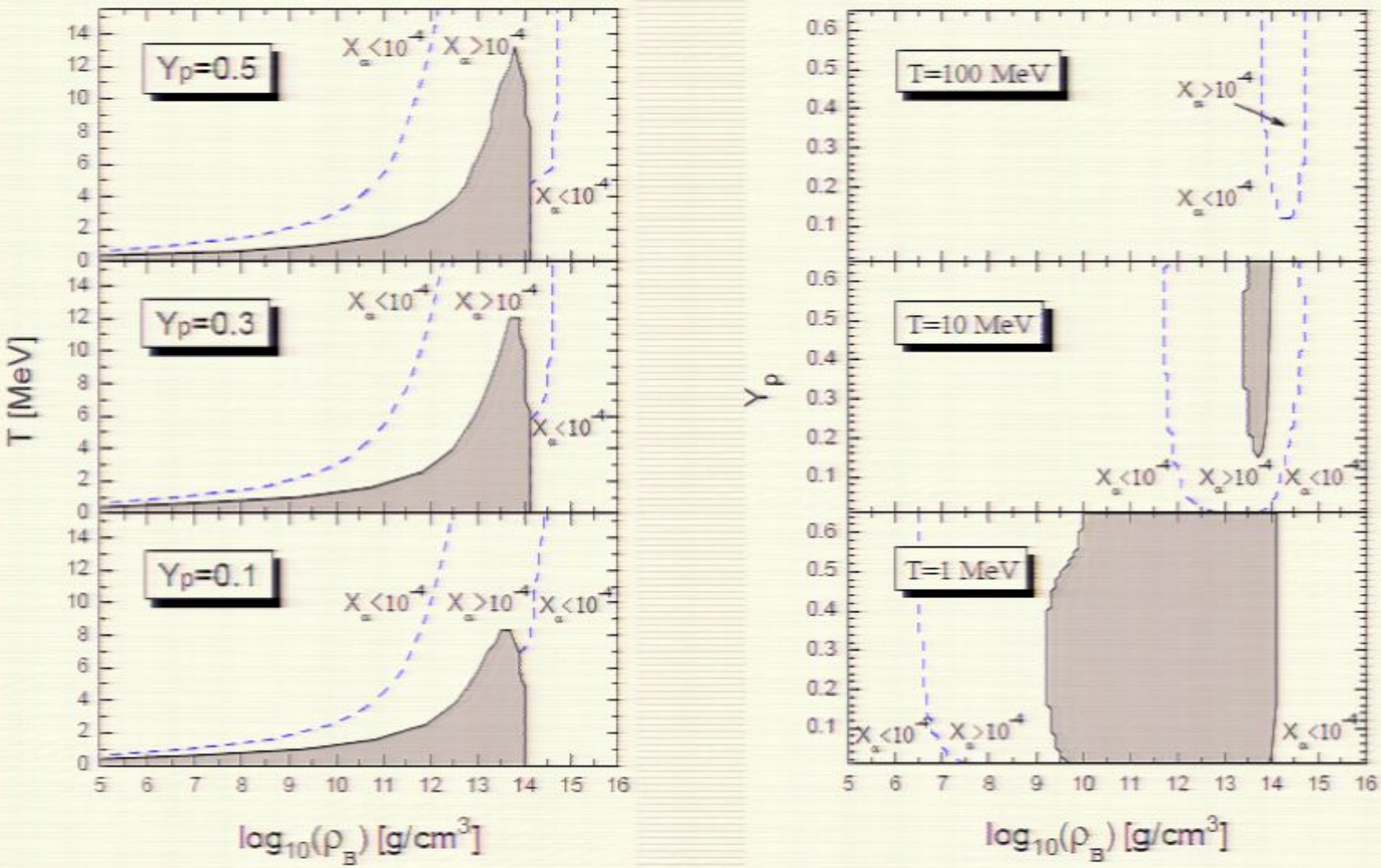


Phase diagrams

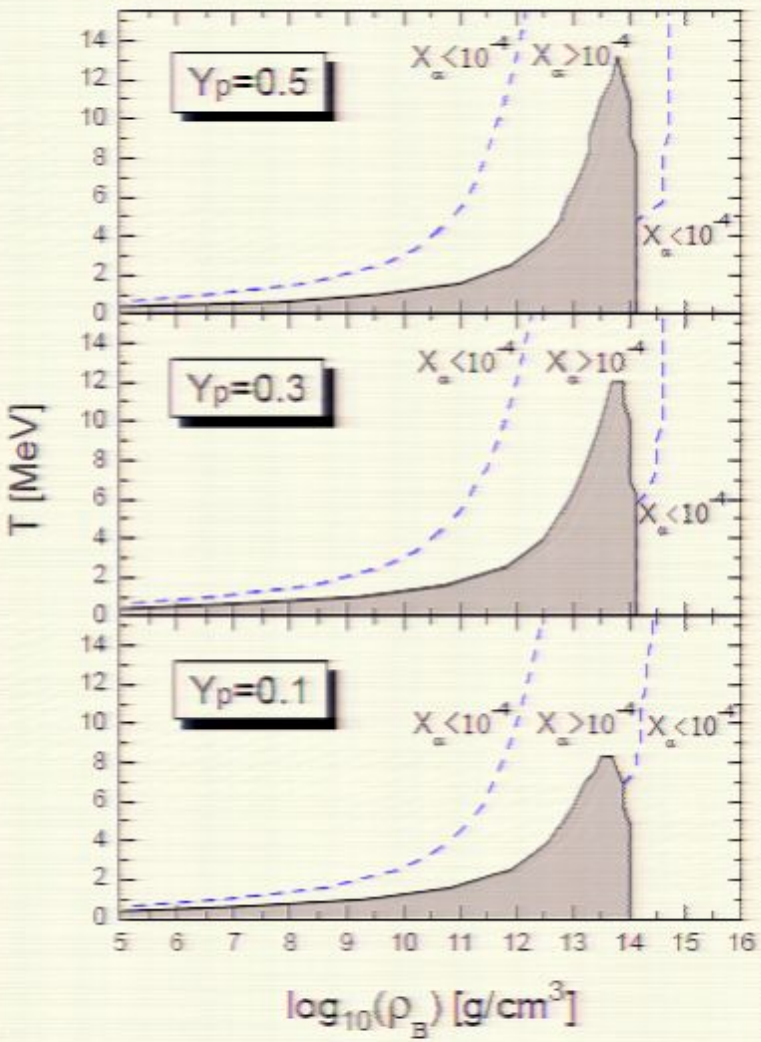


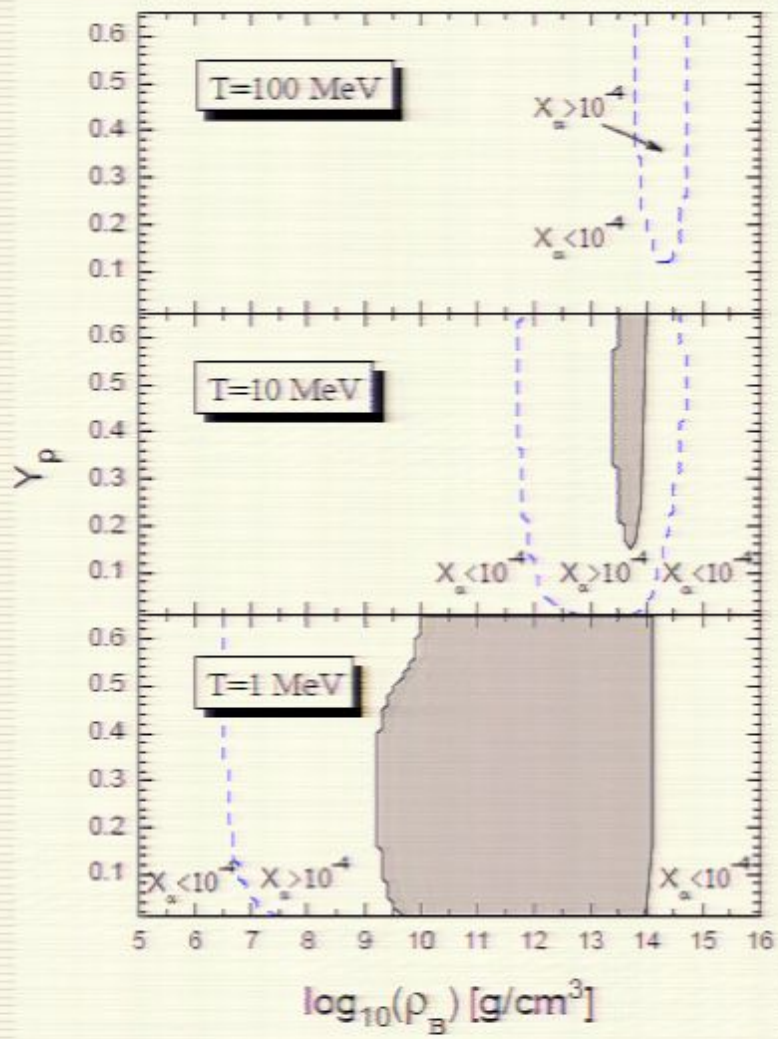


Phase diagrams

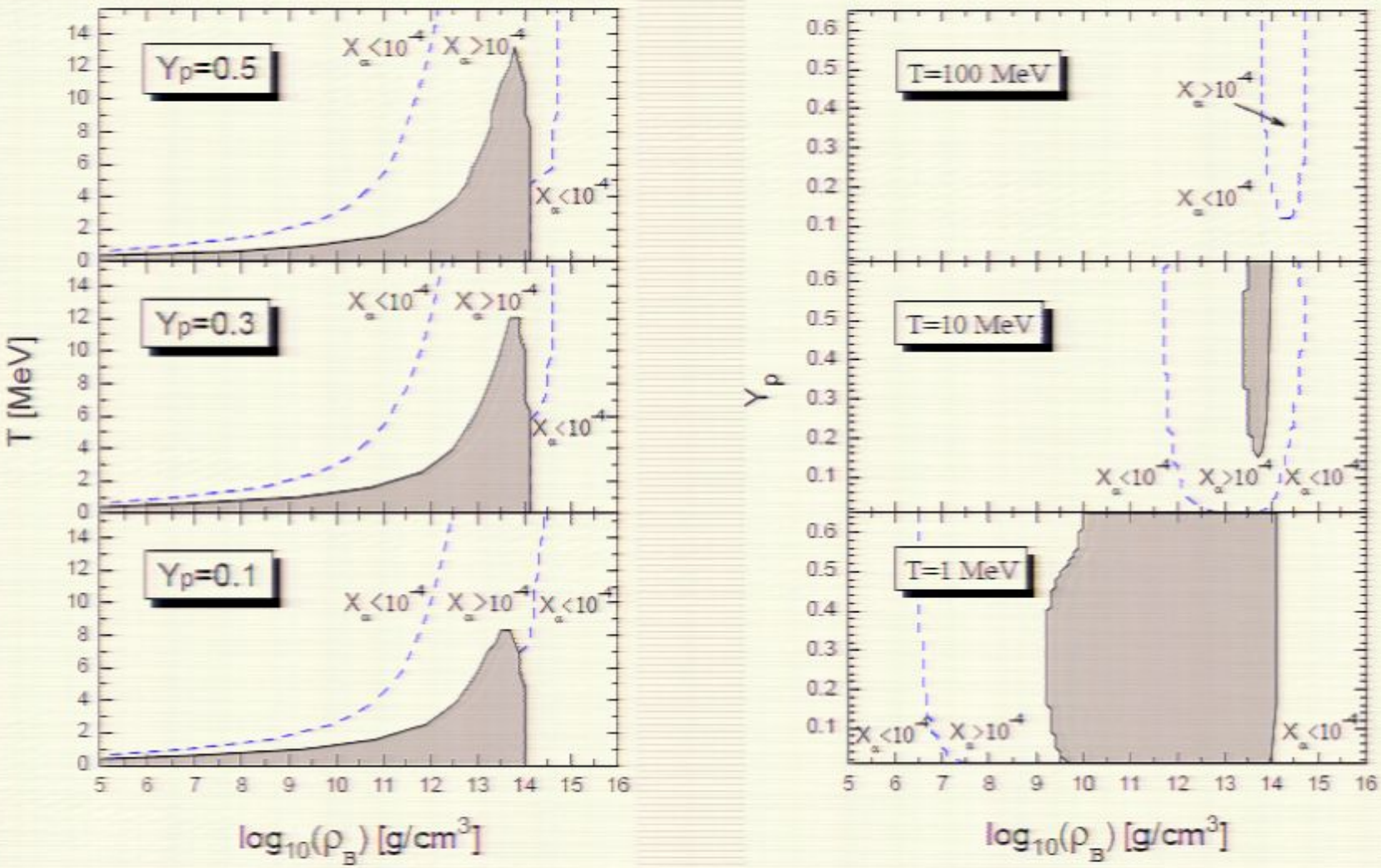


Phase diagrams

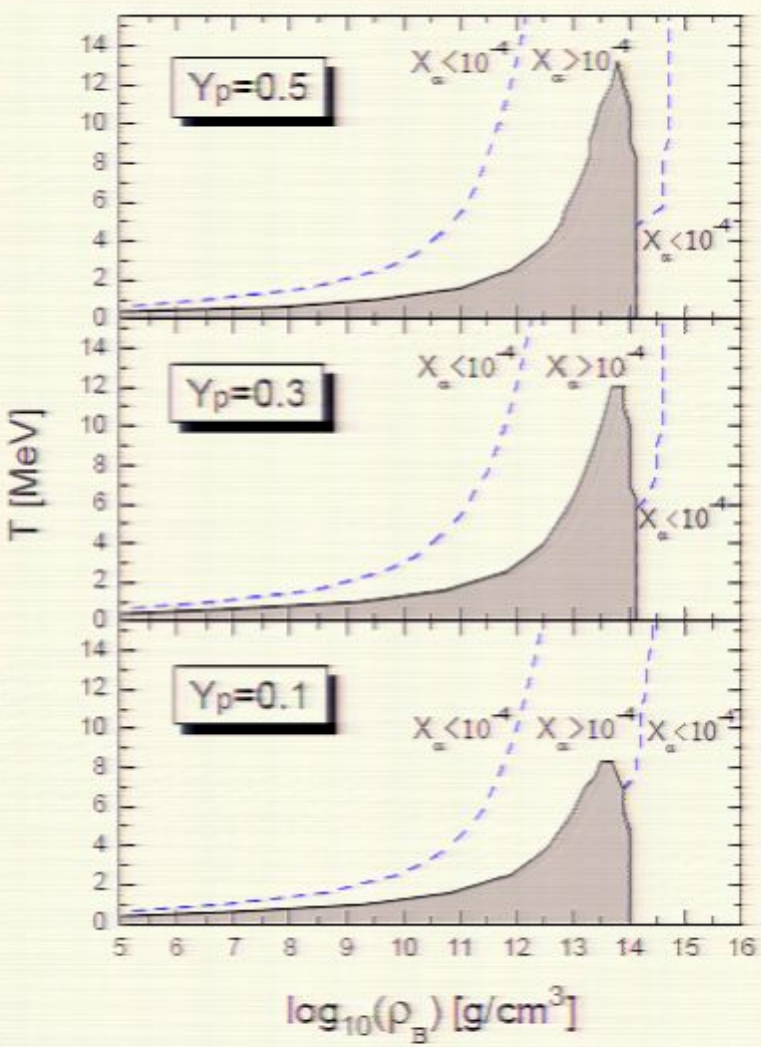


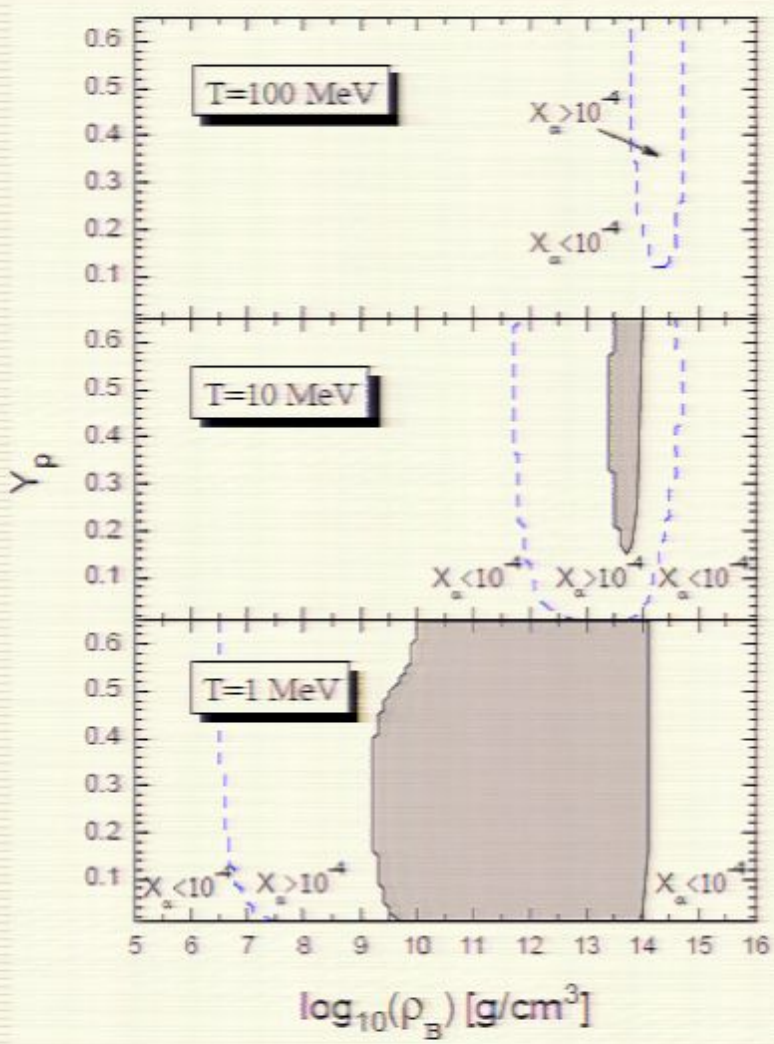


Phase diagrams

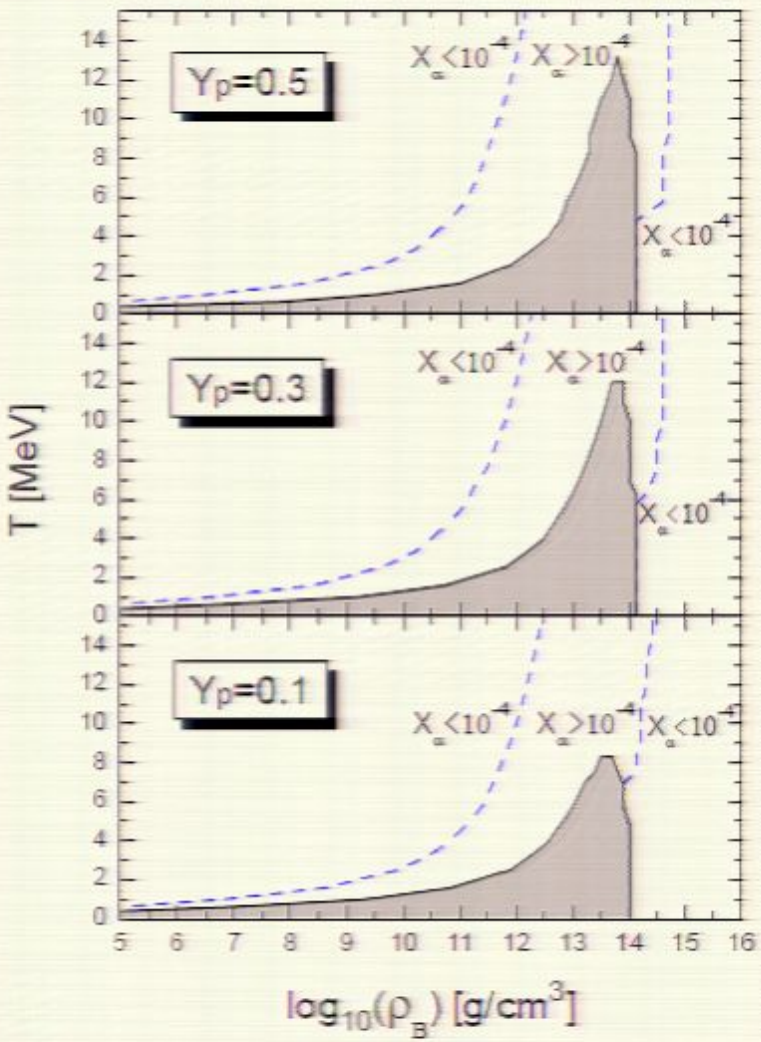


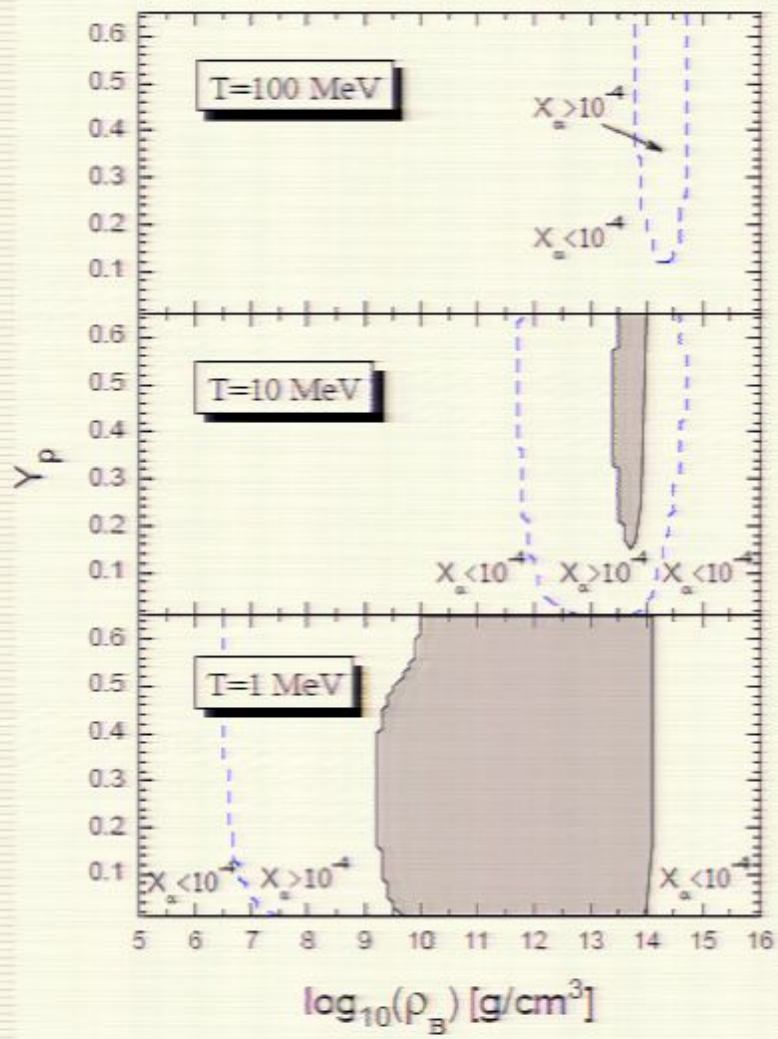
Phase diagrams



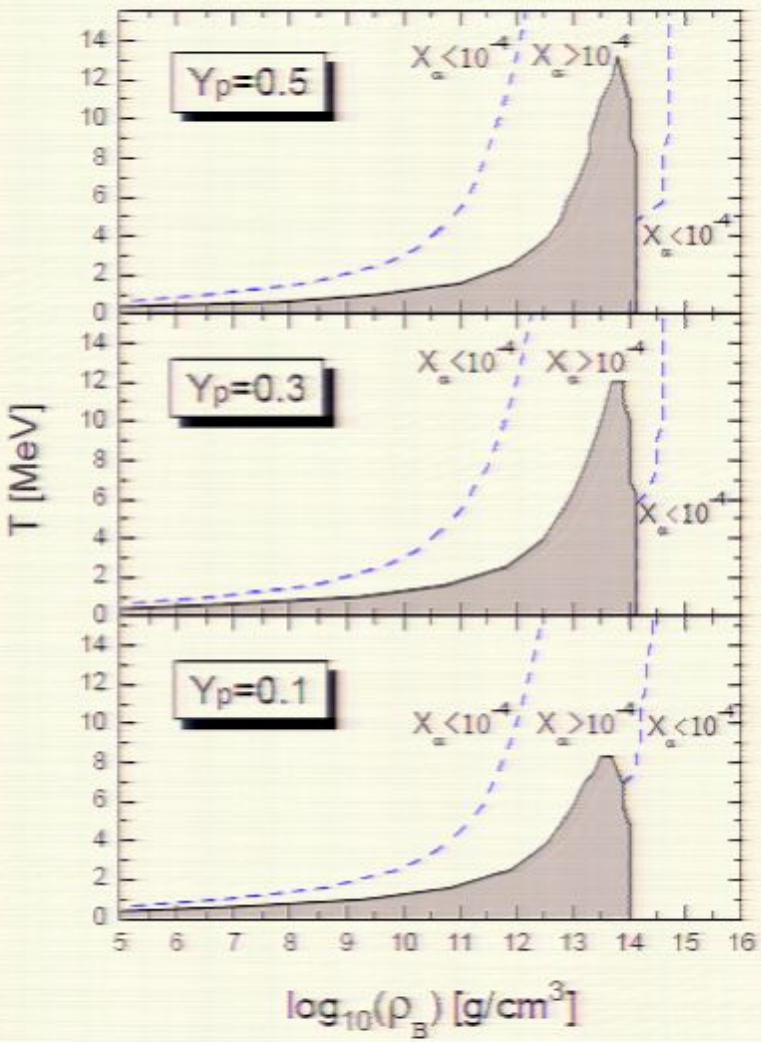


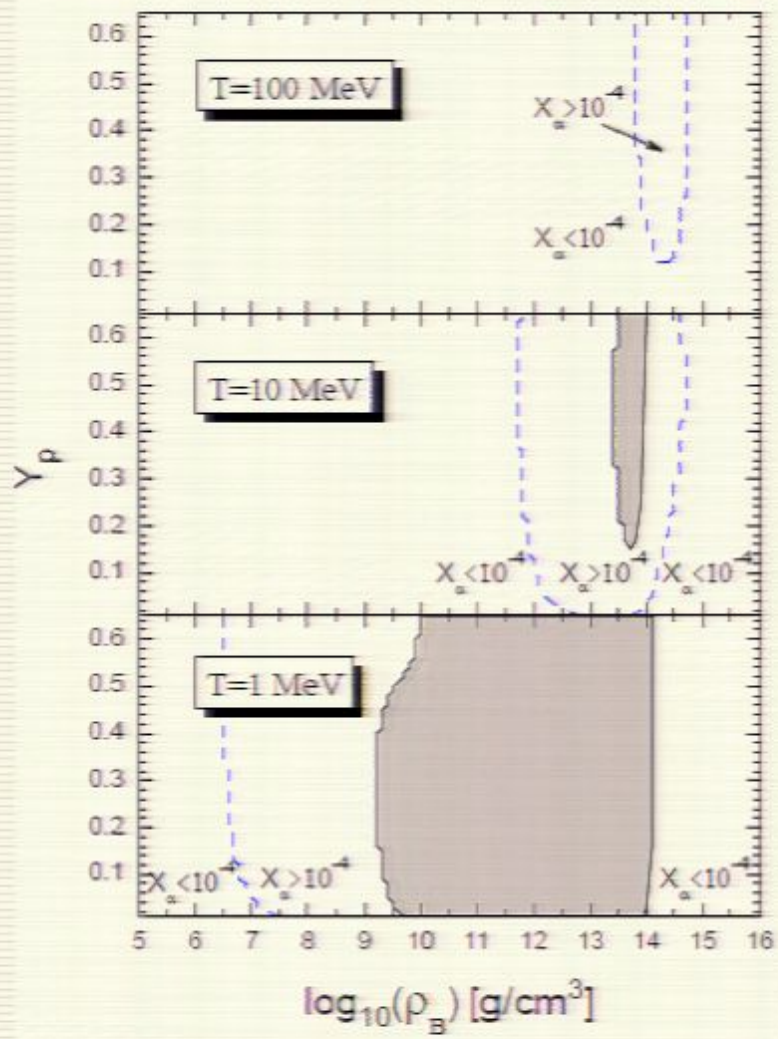
Phase diagrams



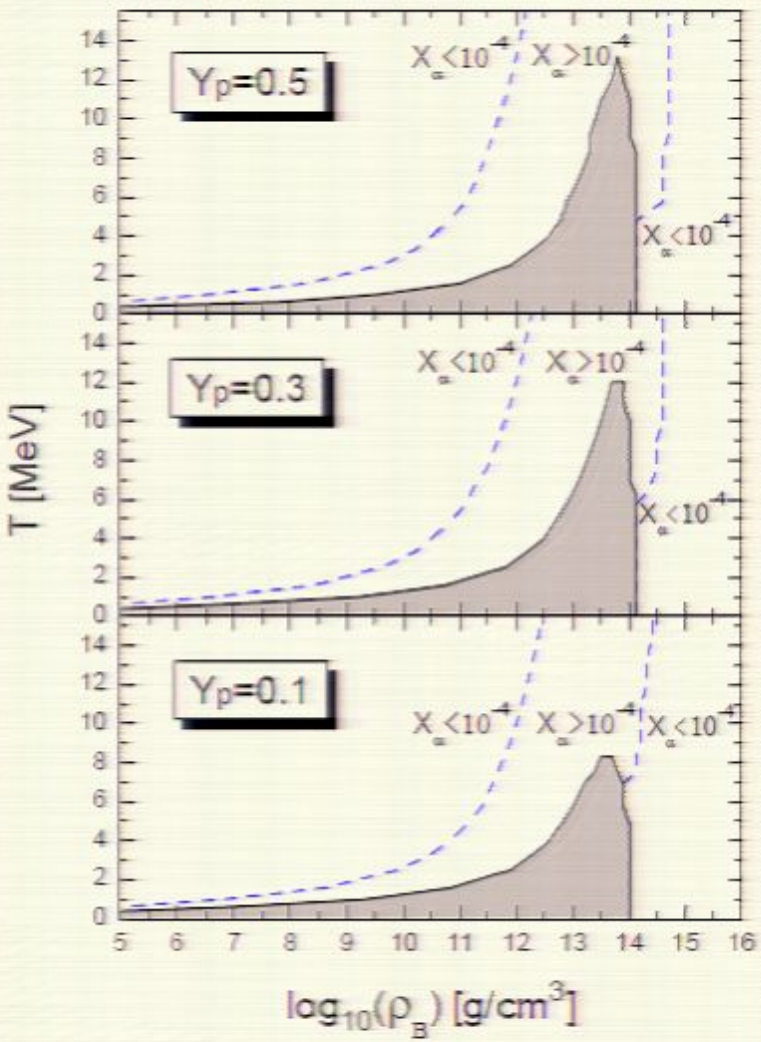


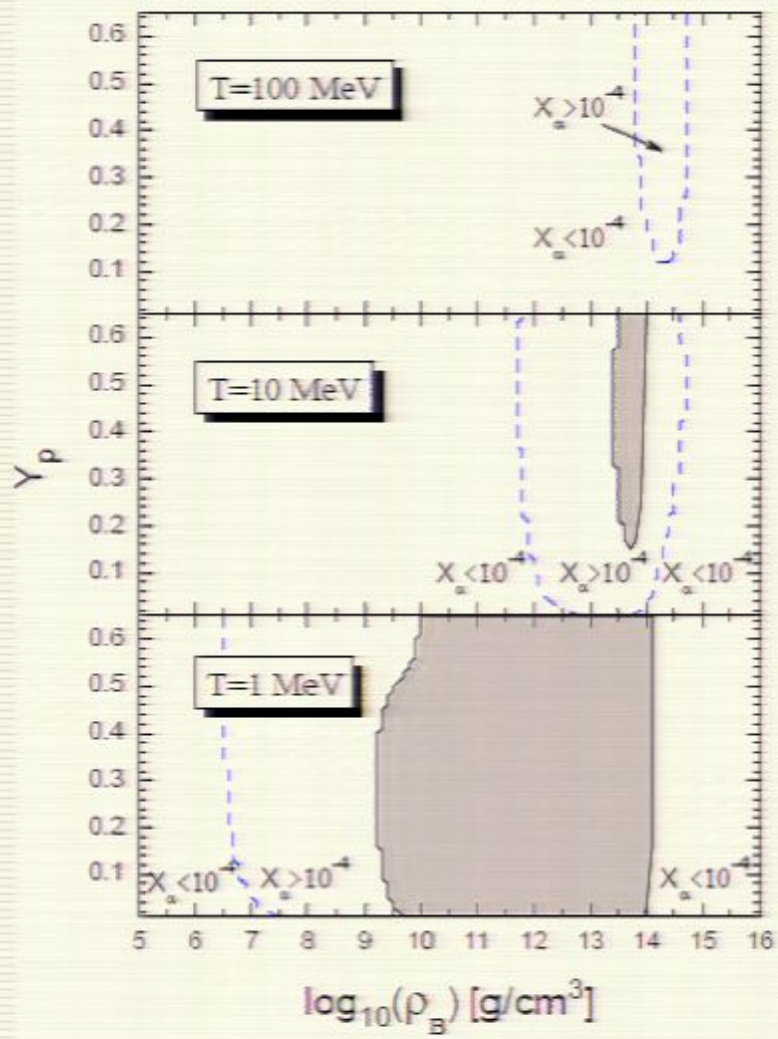
Phase diagrams



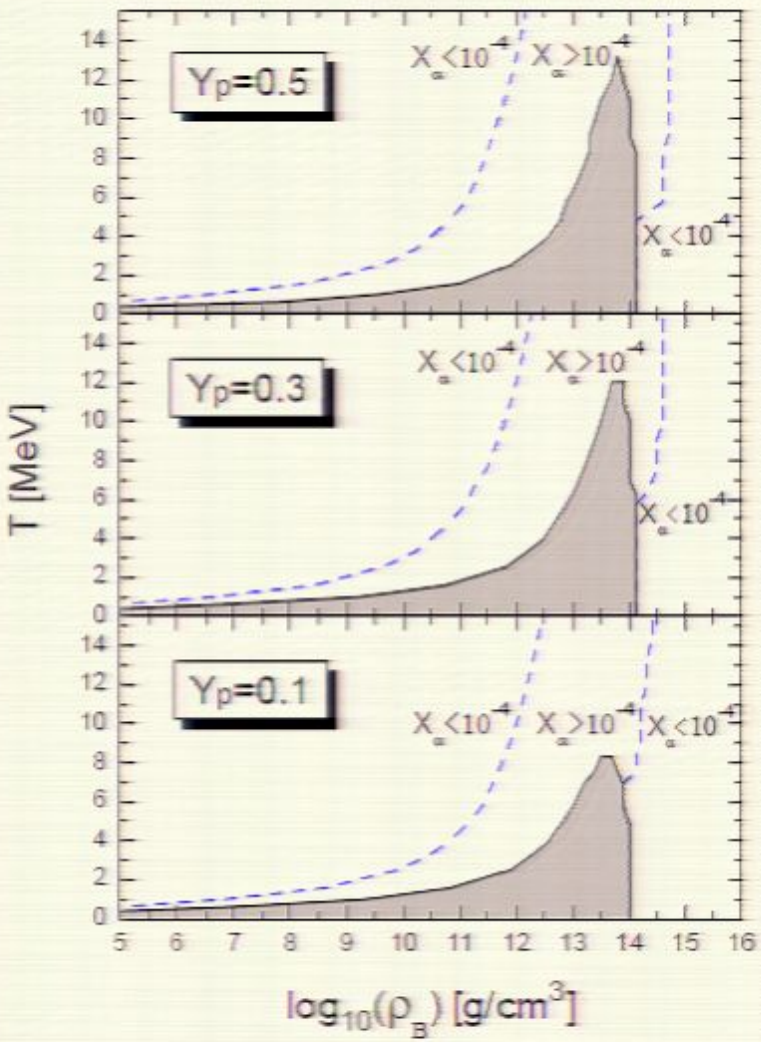


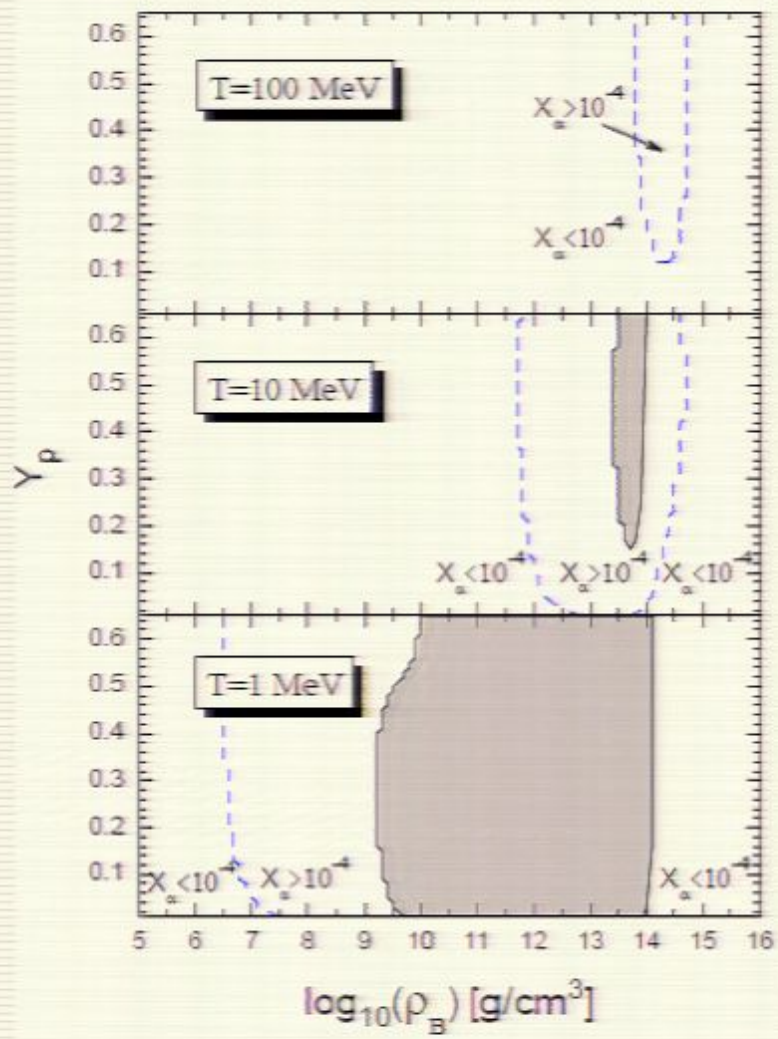
Phase diagrams



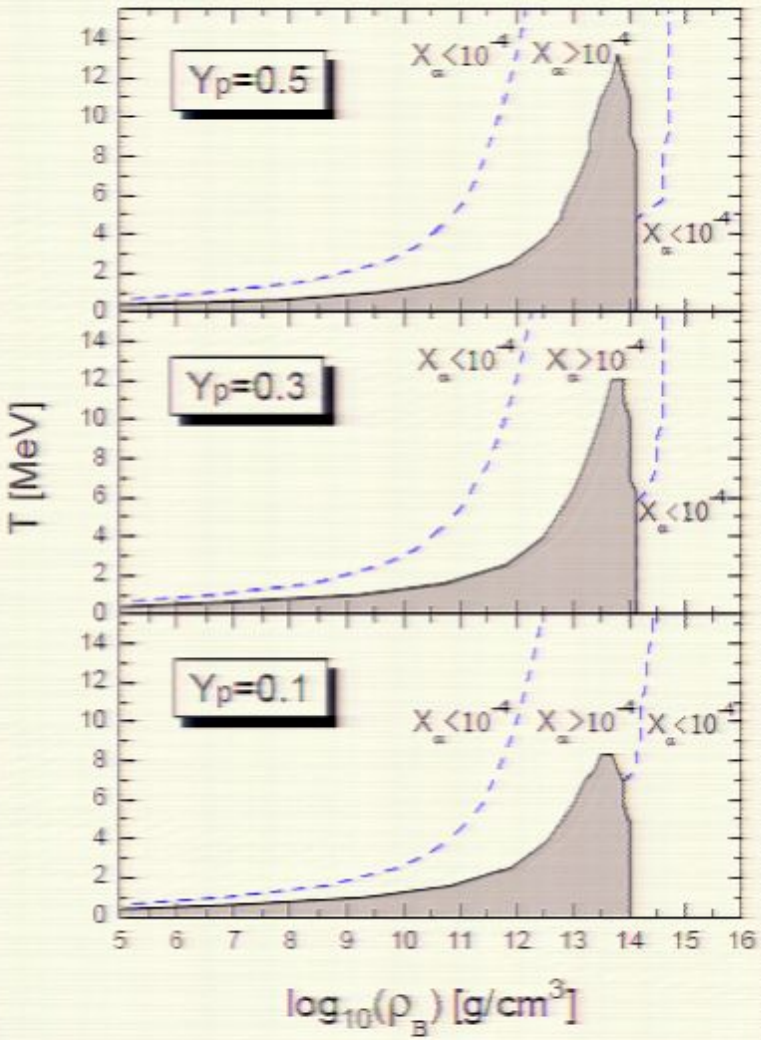


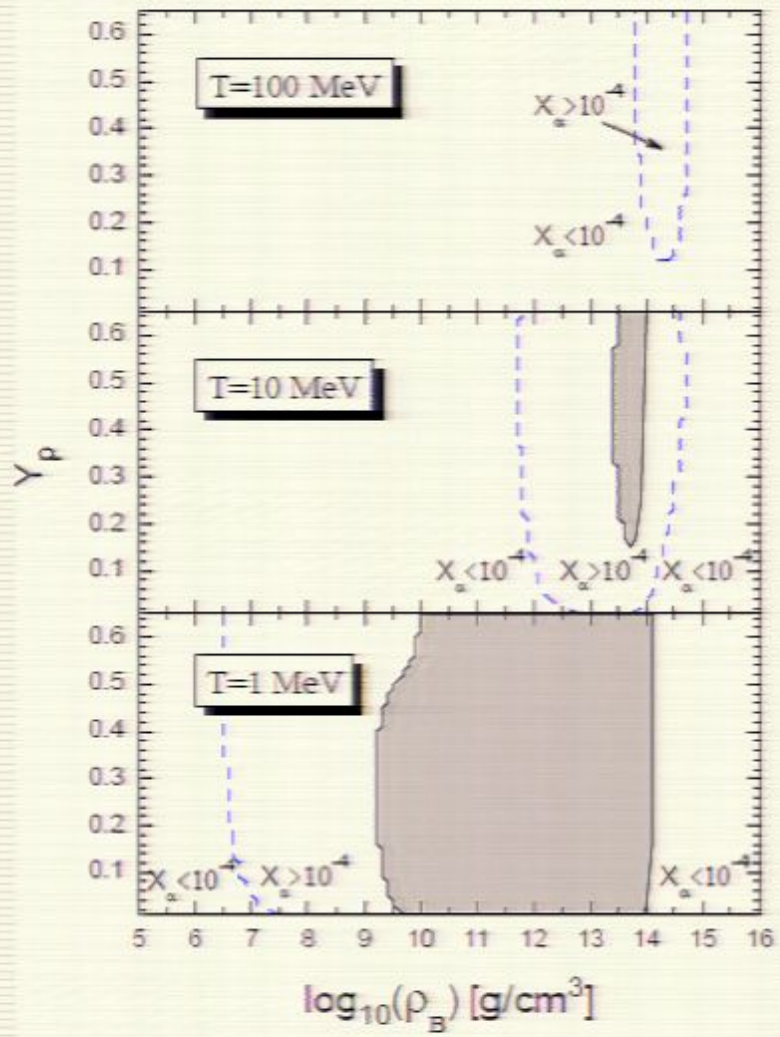
Phase diagrams



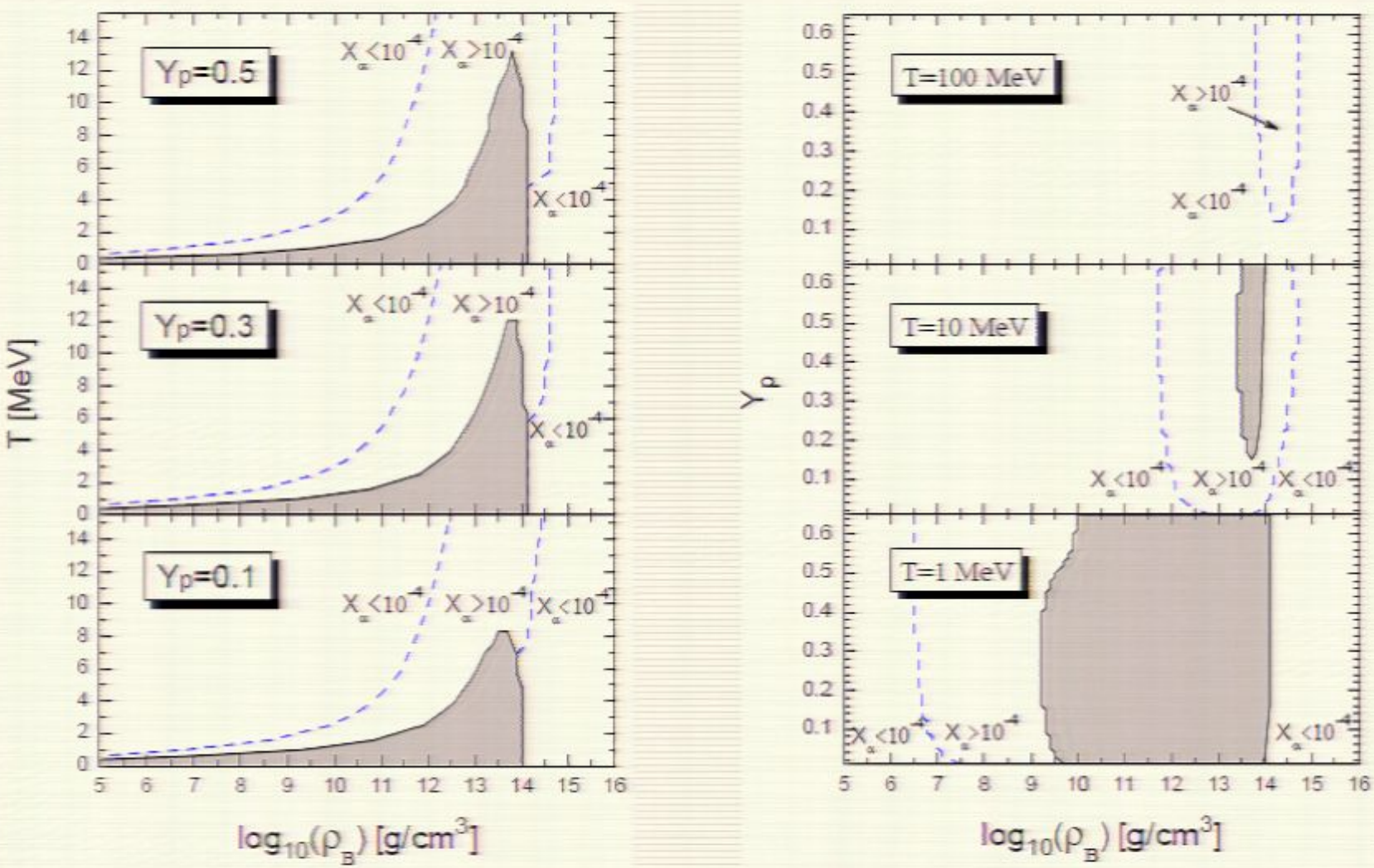


Phase diagrams

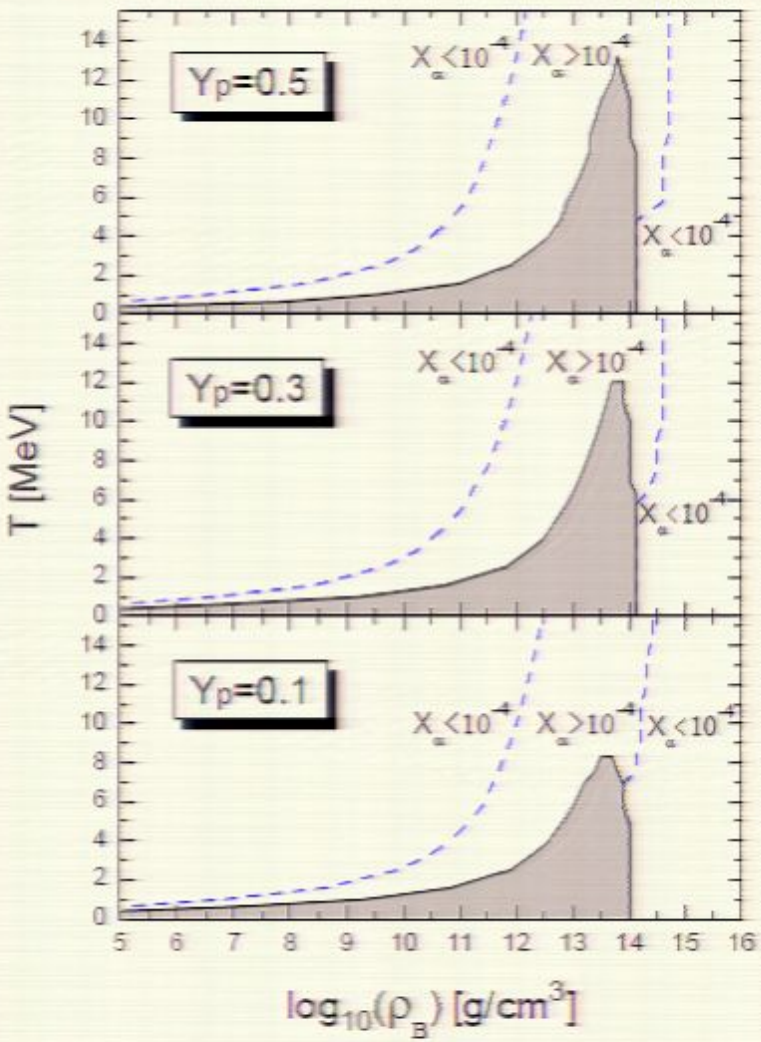


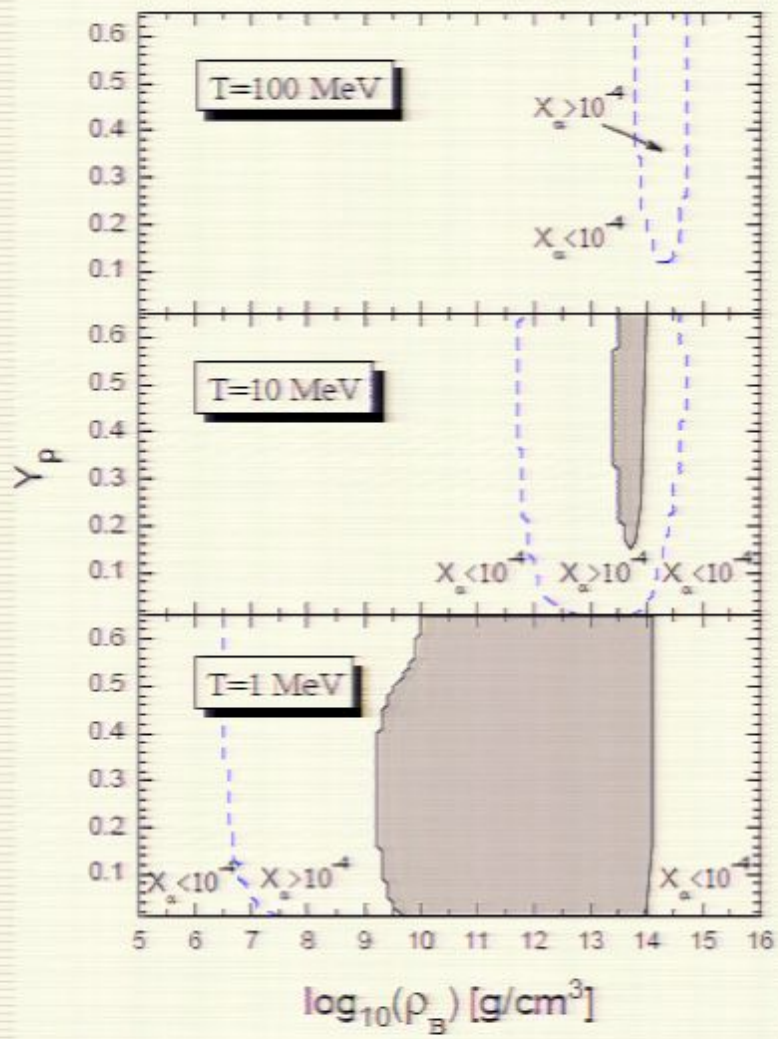


Phase diagrams

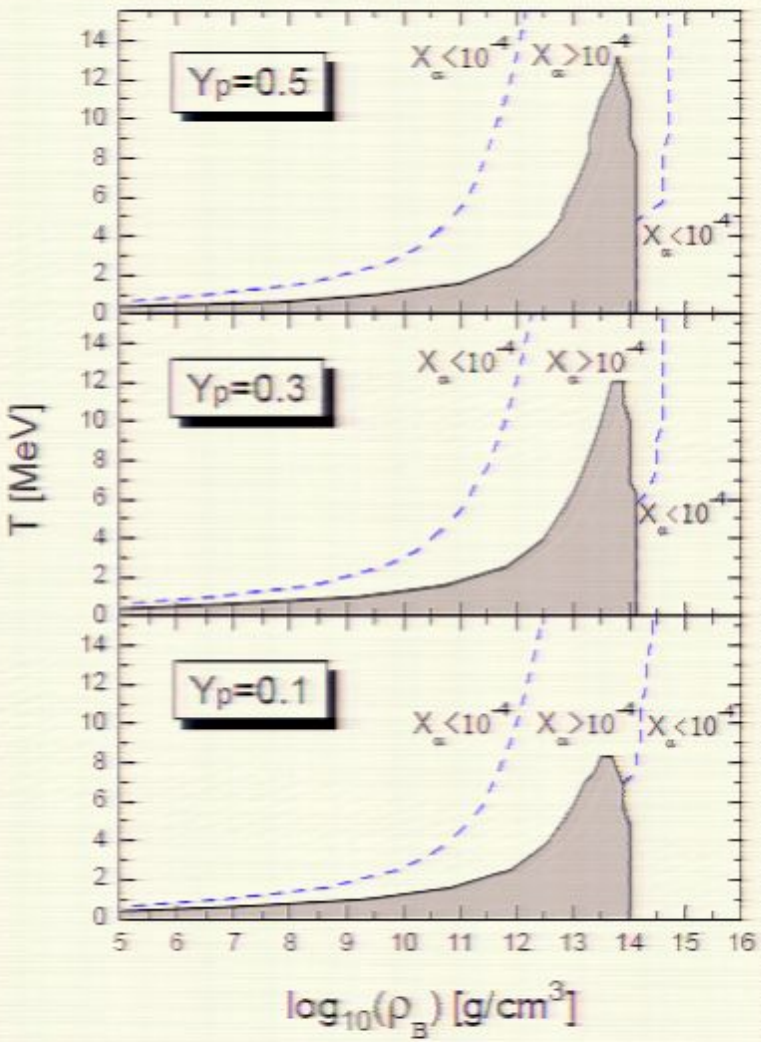


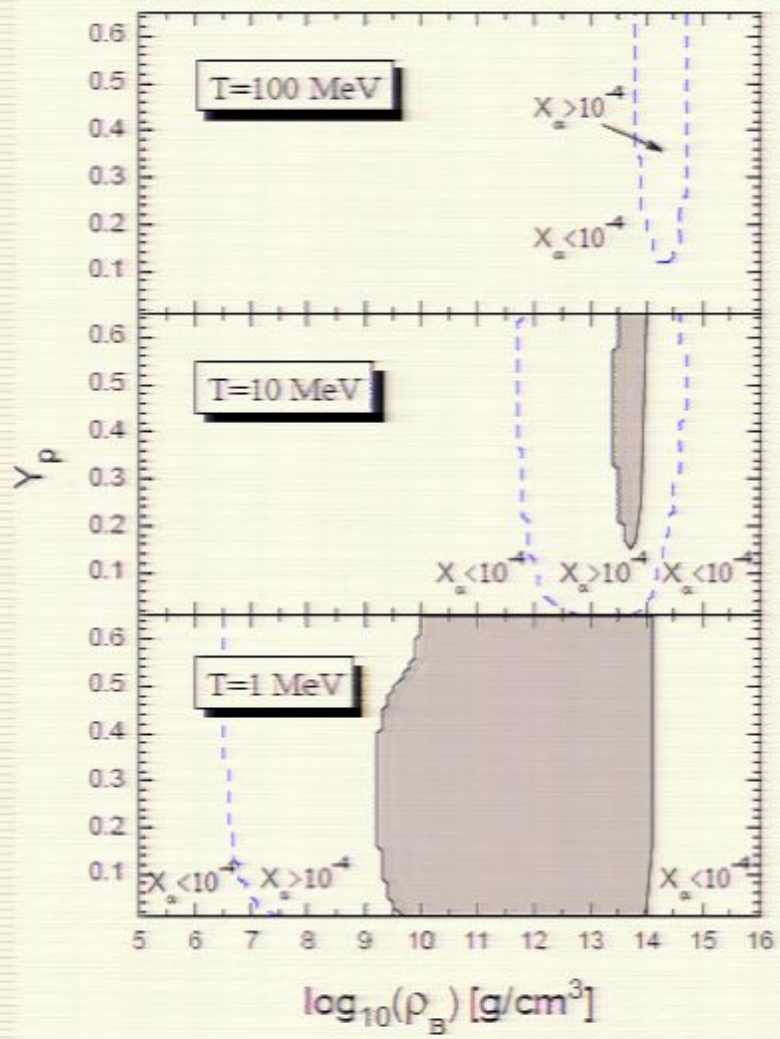
Phase diagrams



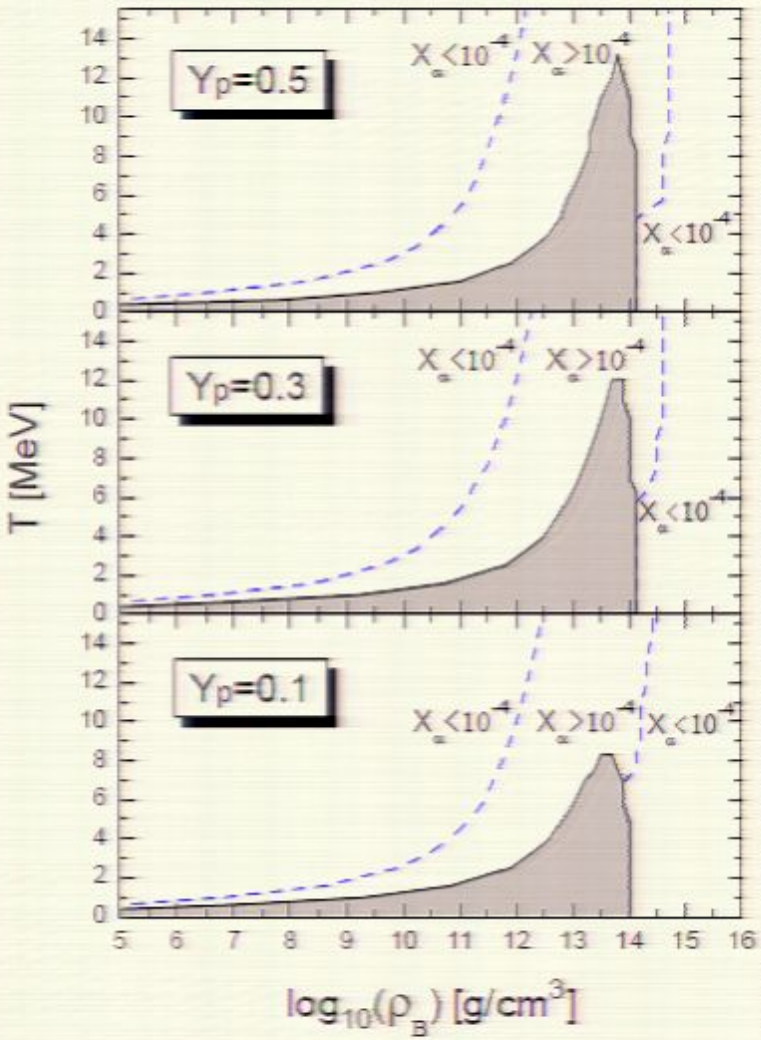


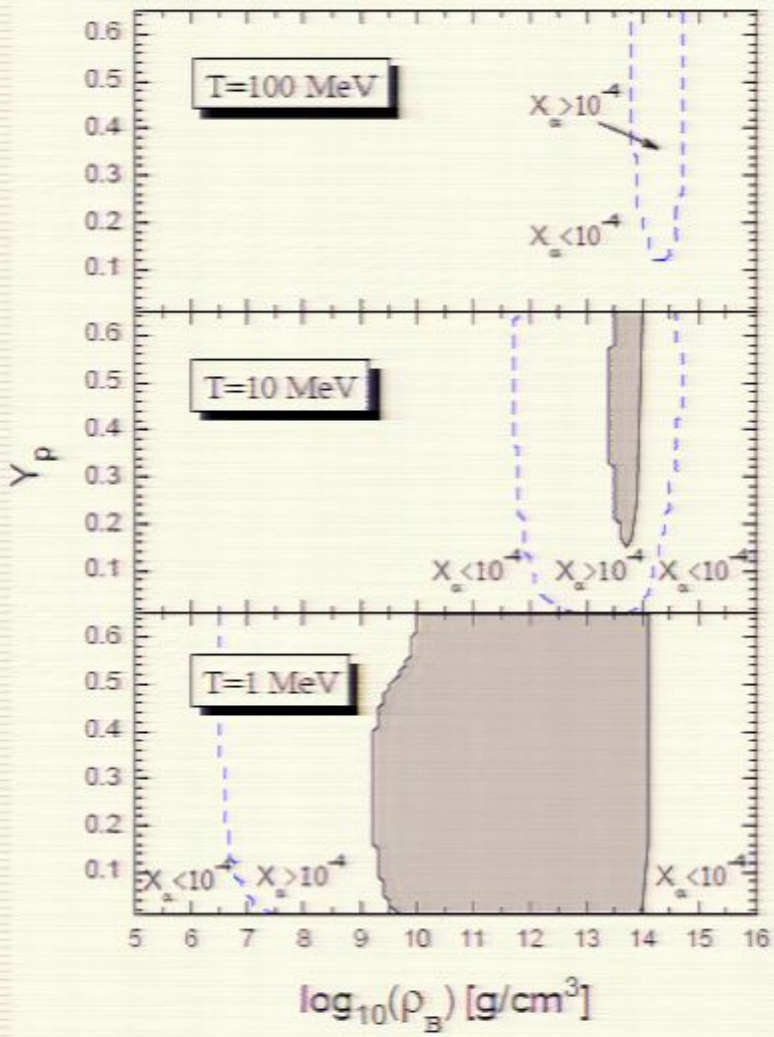
Phase diagrams



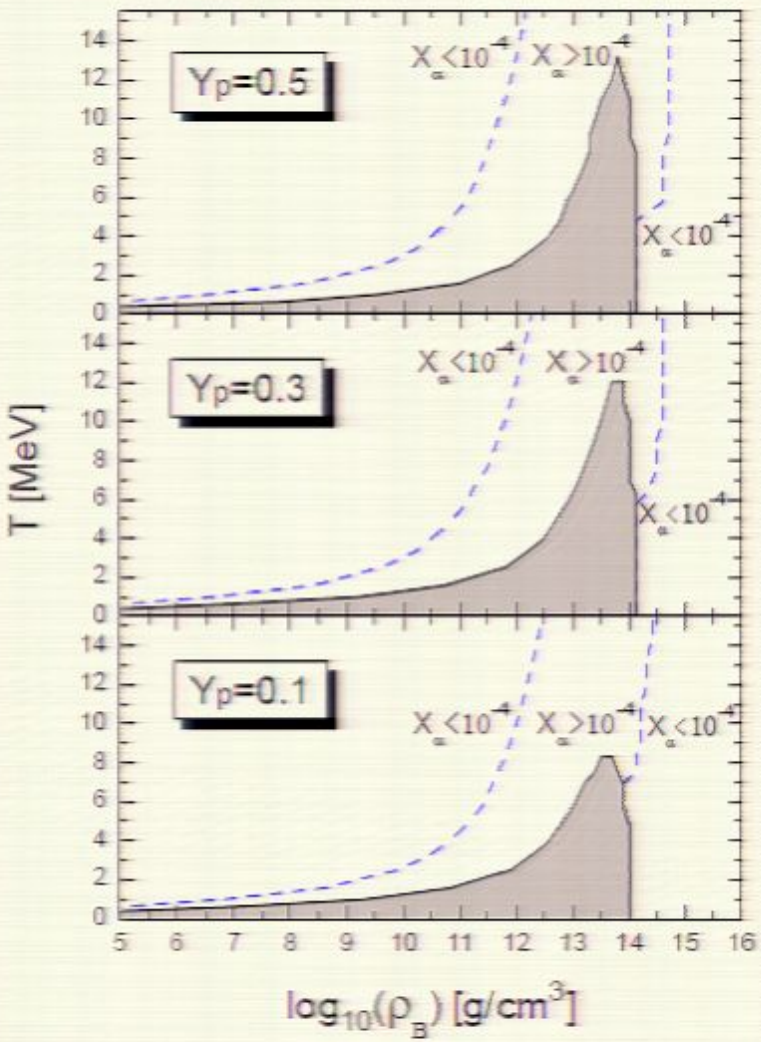


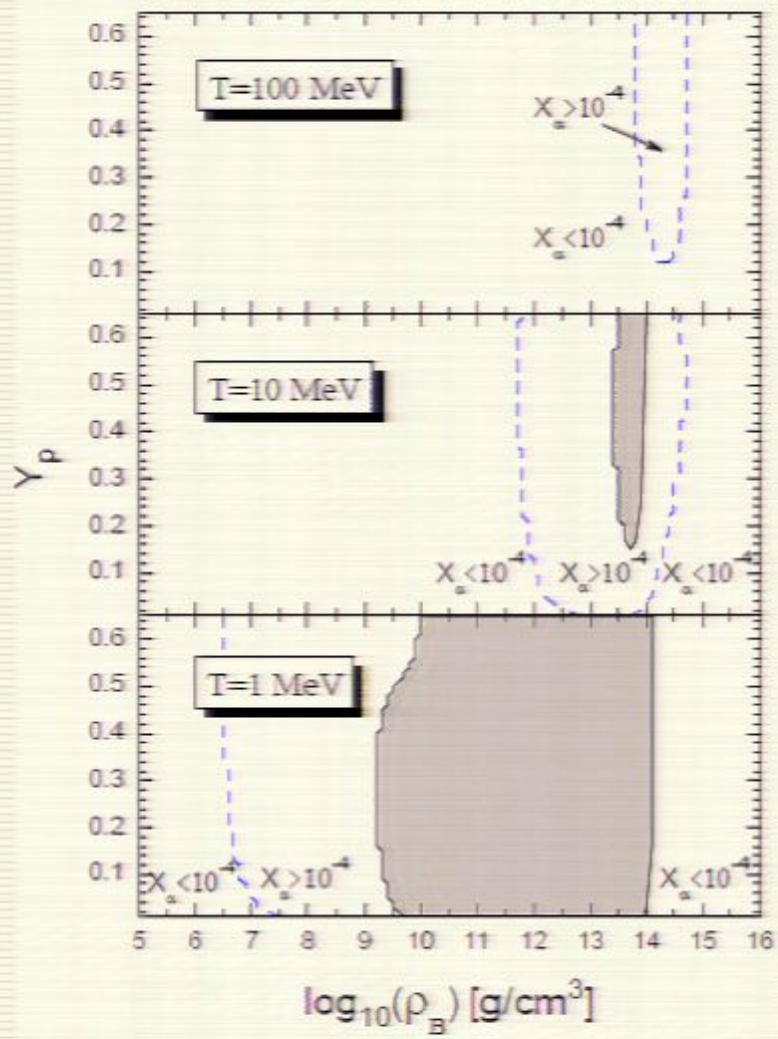
Phase diagrams



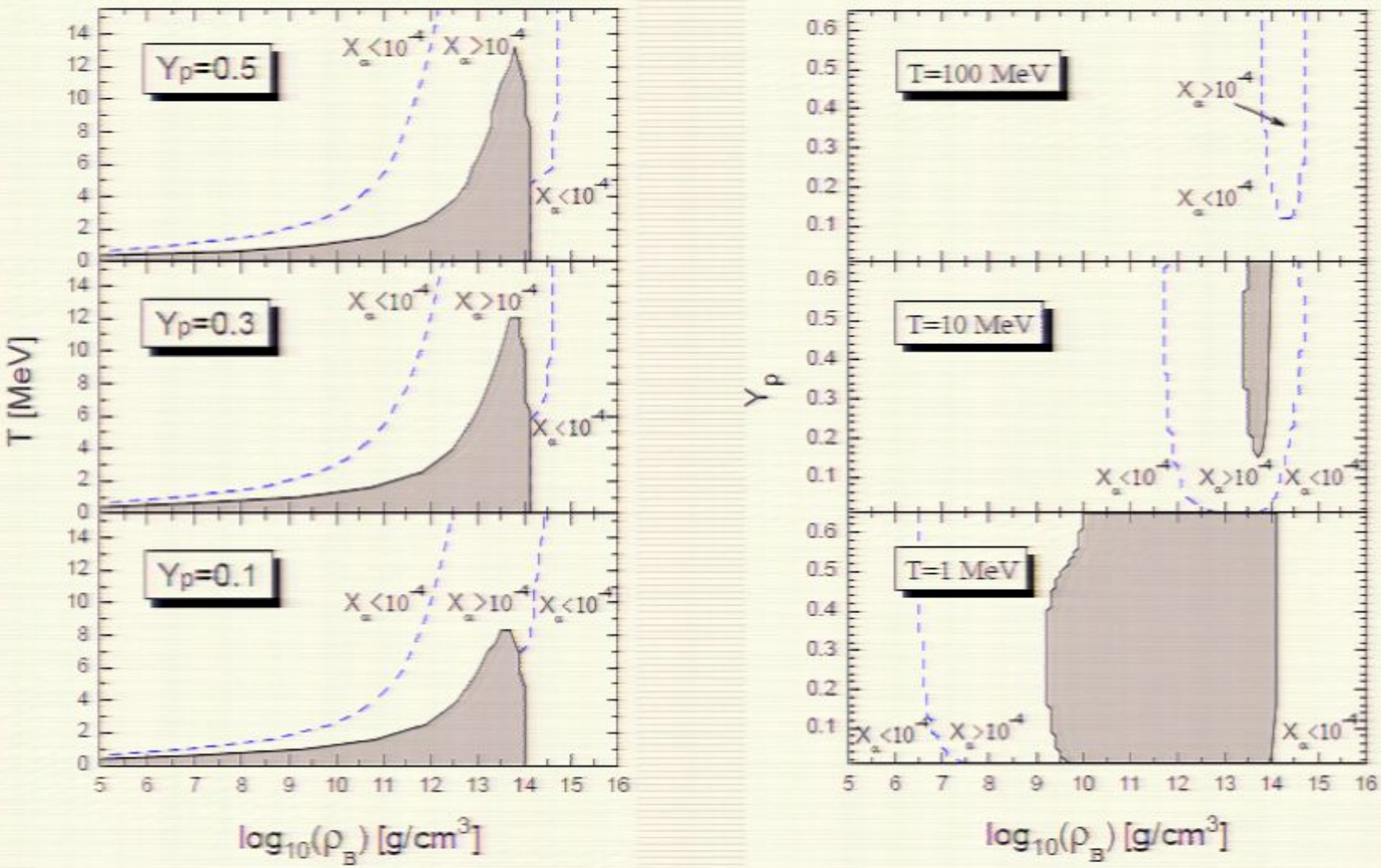


Phase diagrams

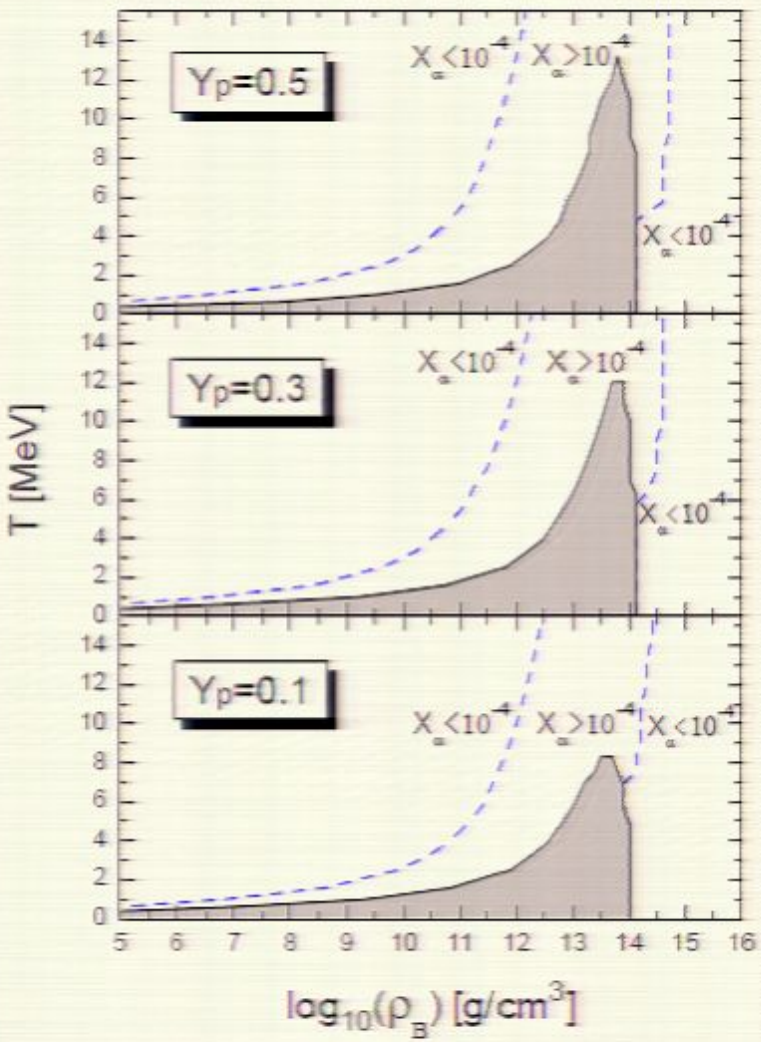


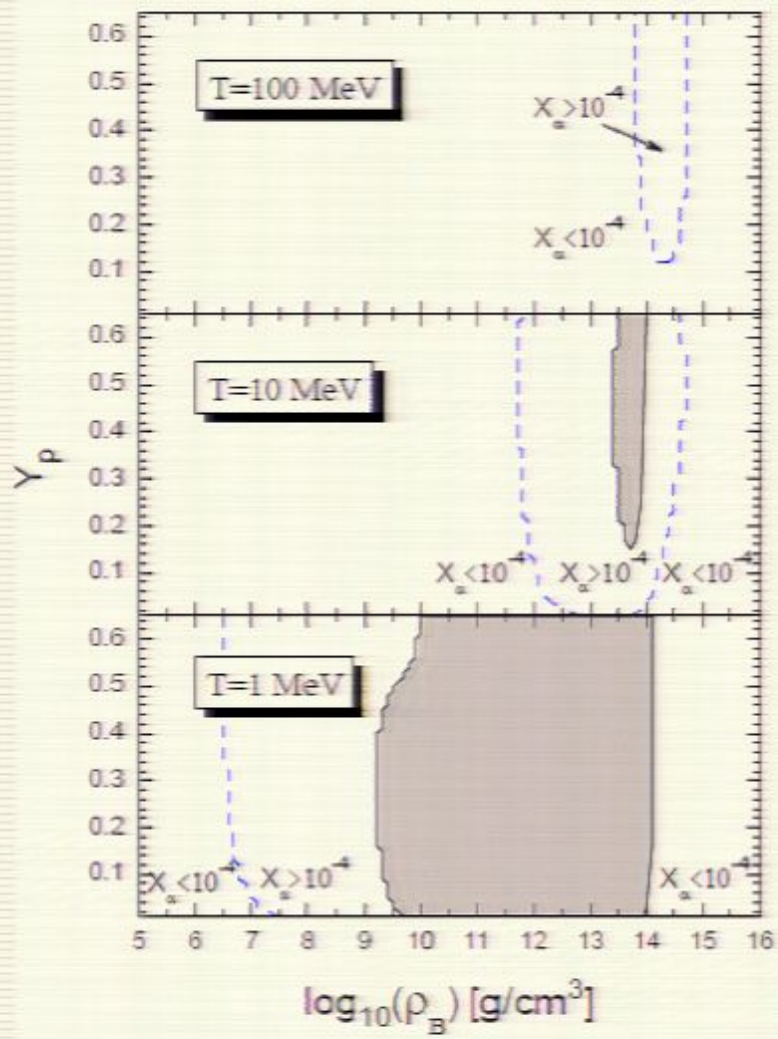


Phase diagrams

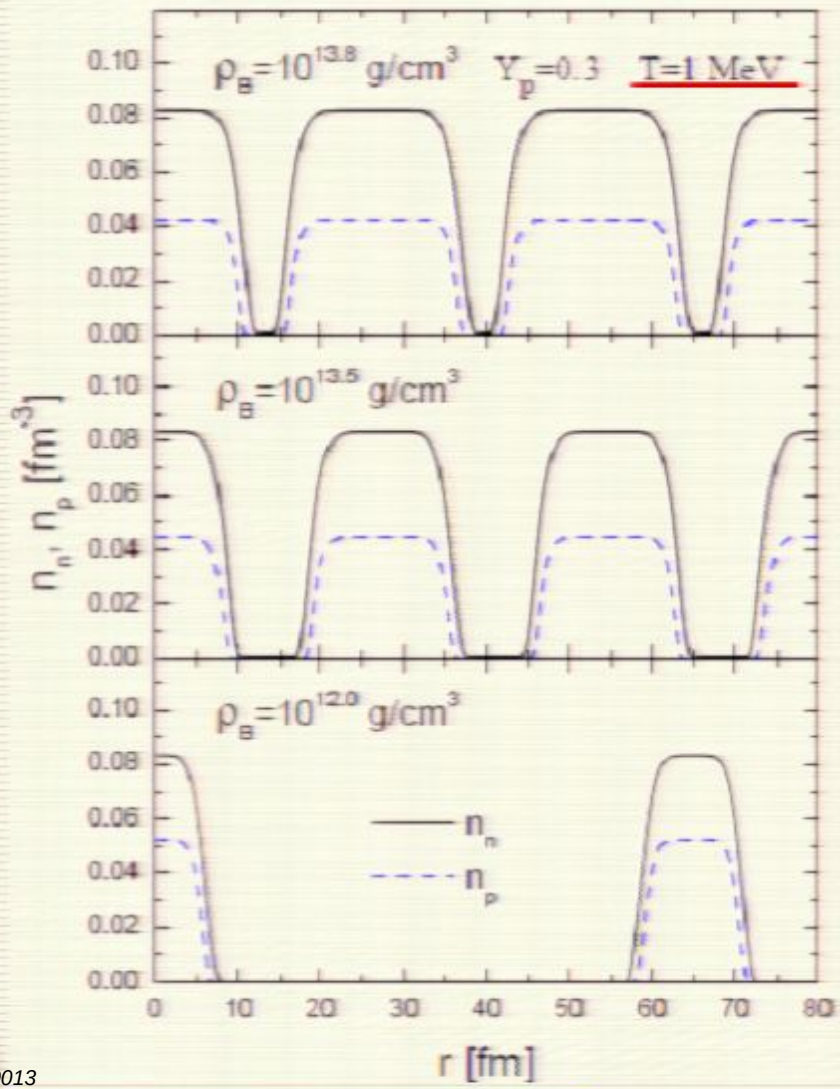


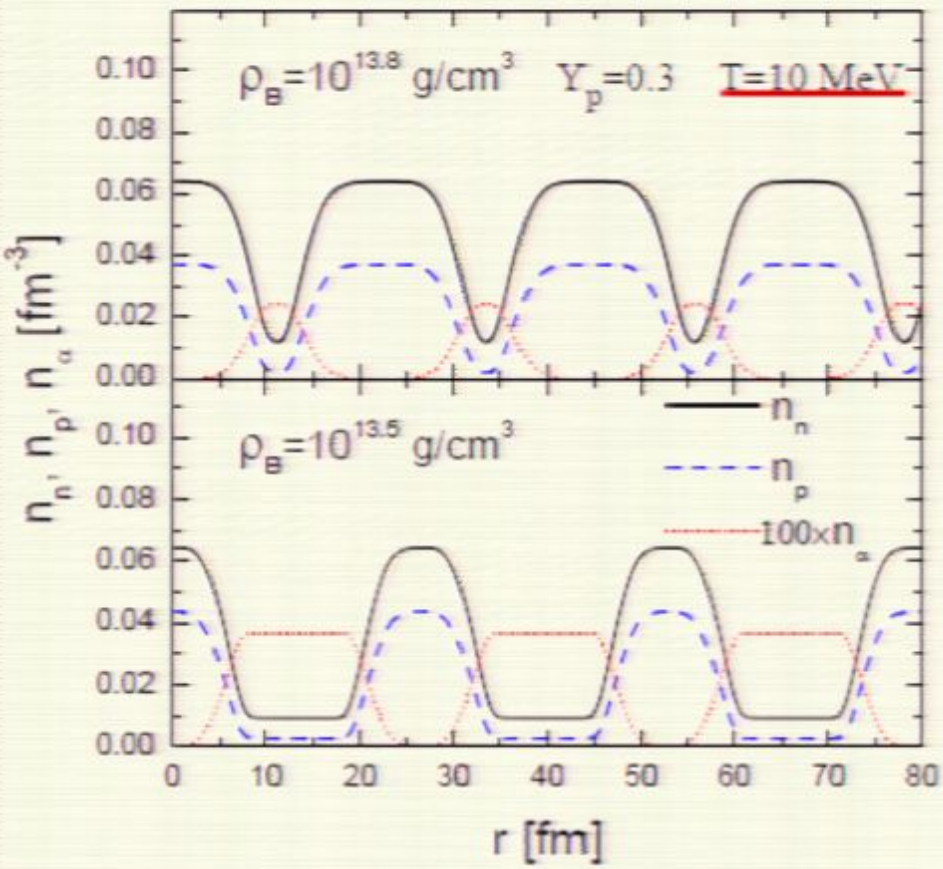
Phase diagrams



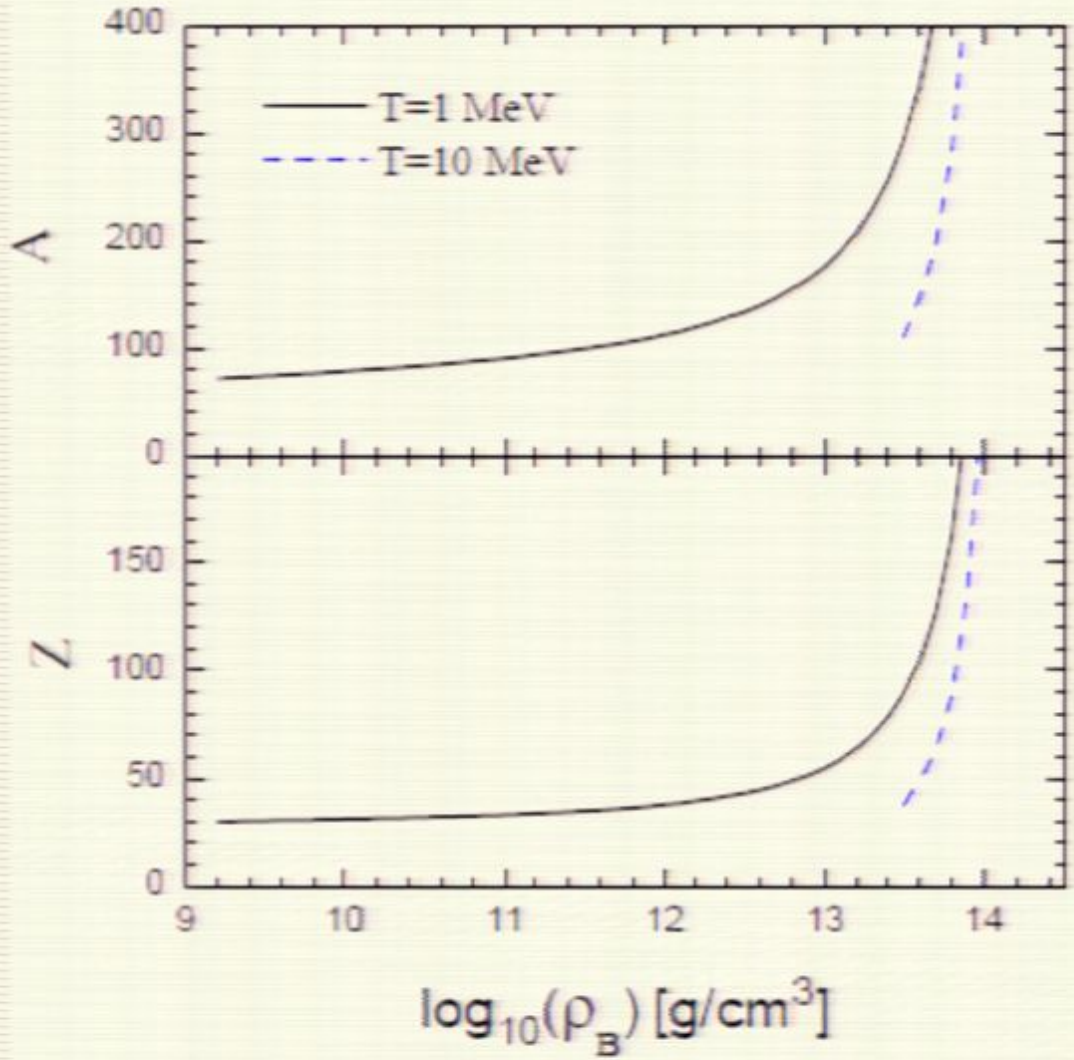


Distributions in non-uniform matter



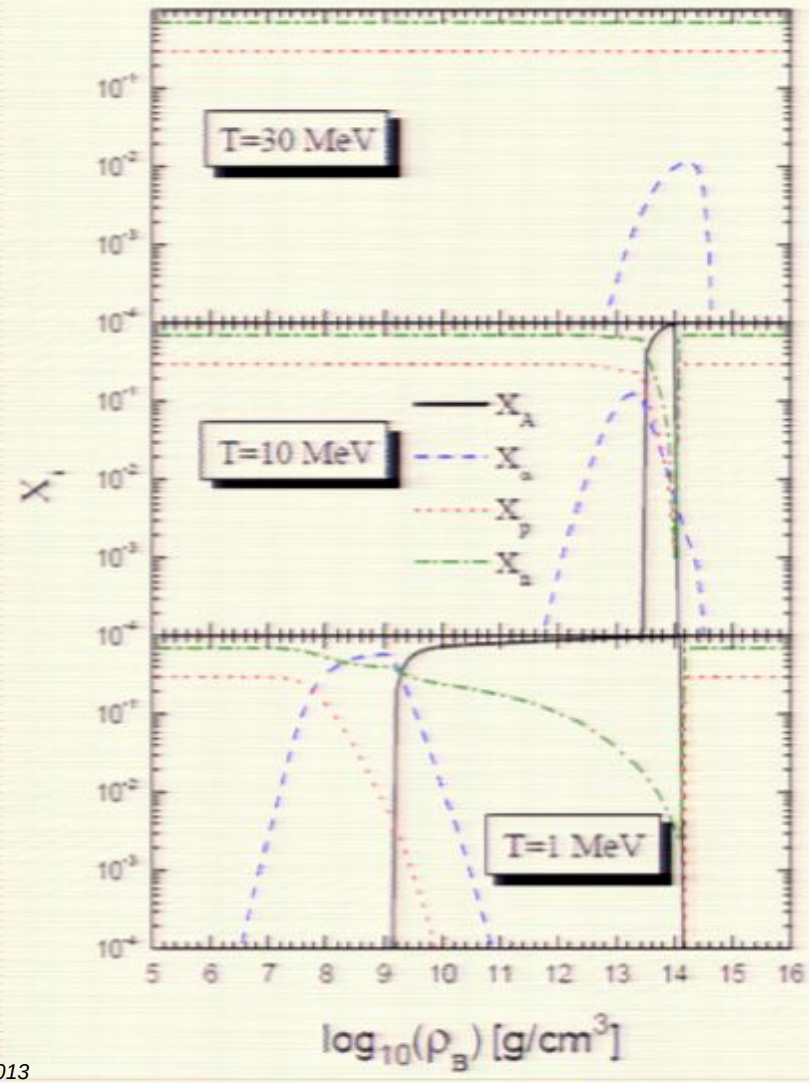


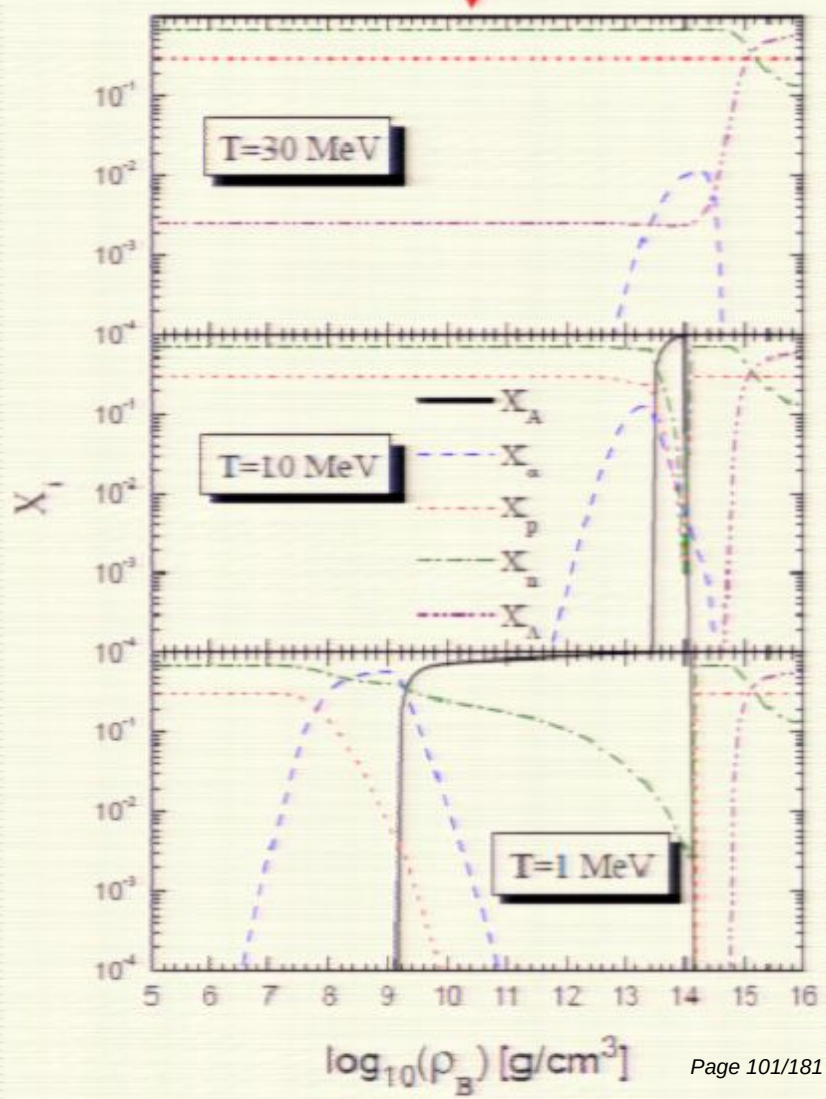
Heavy nuclei in non-uniform matter



Fractions of components

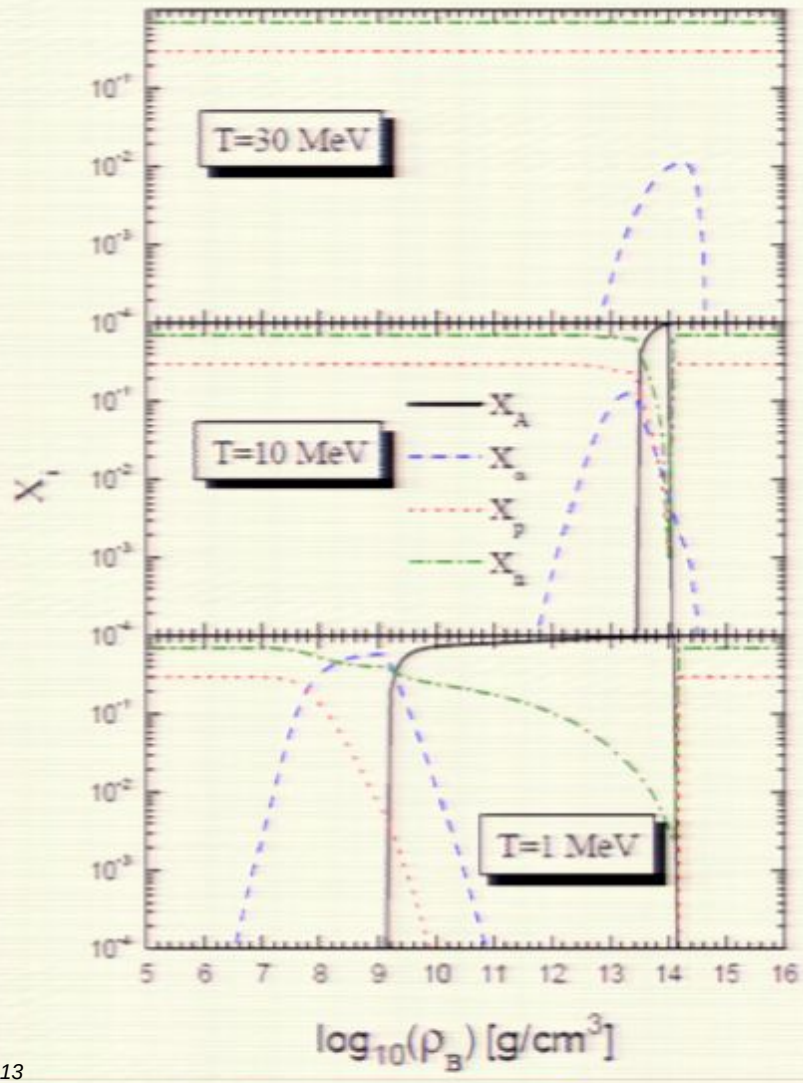
with Λ hyperons

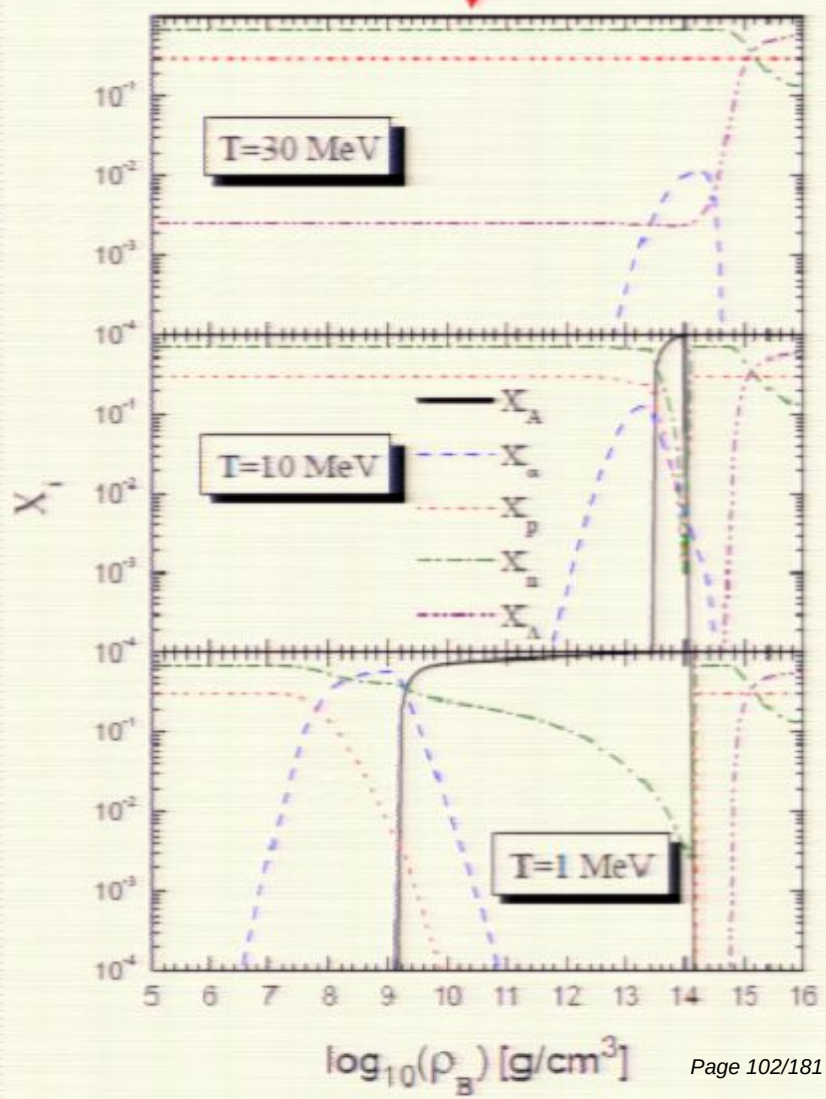




Fractions of components

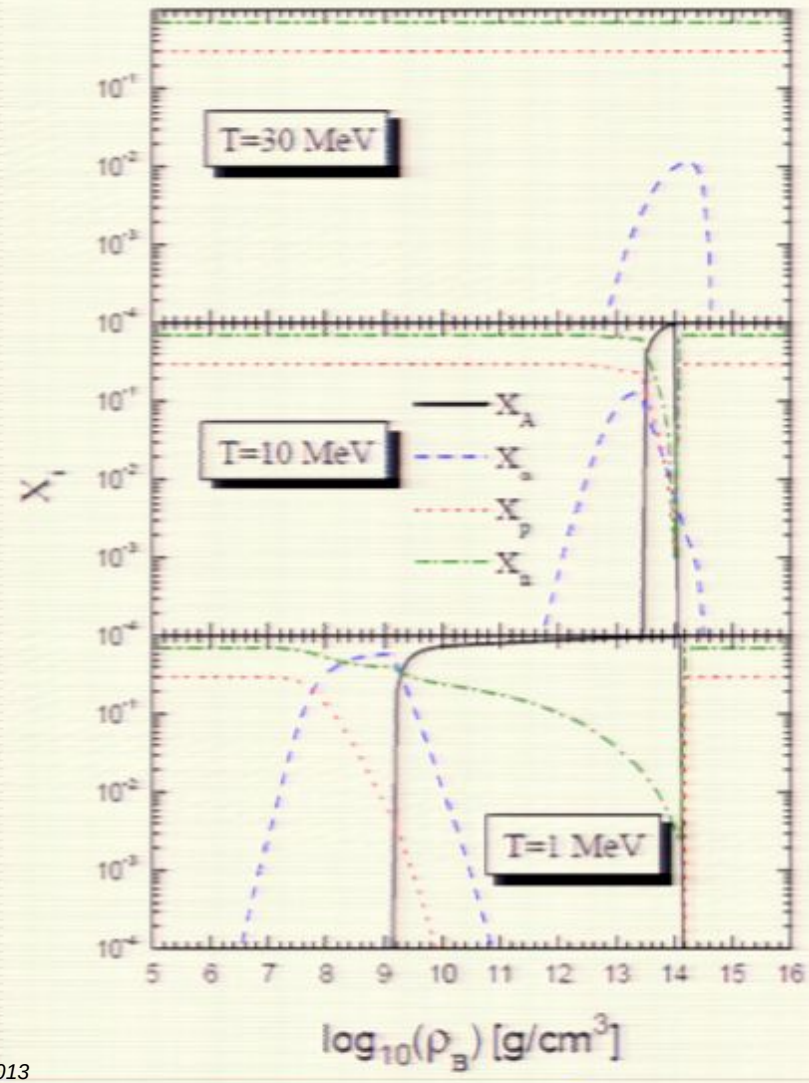
with Λ hyperons

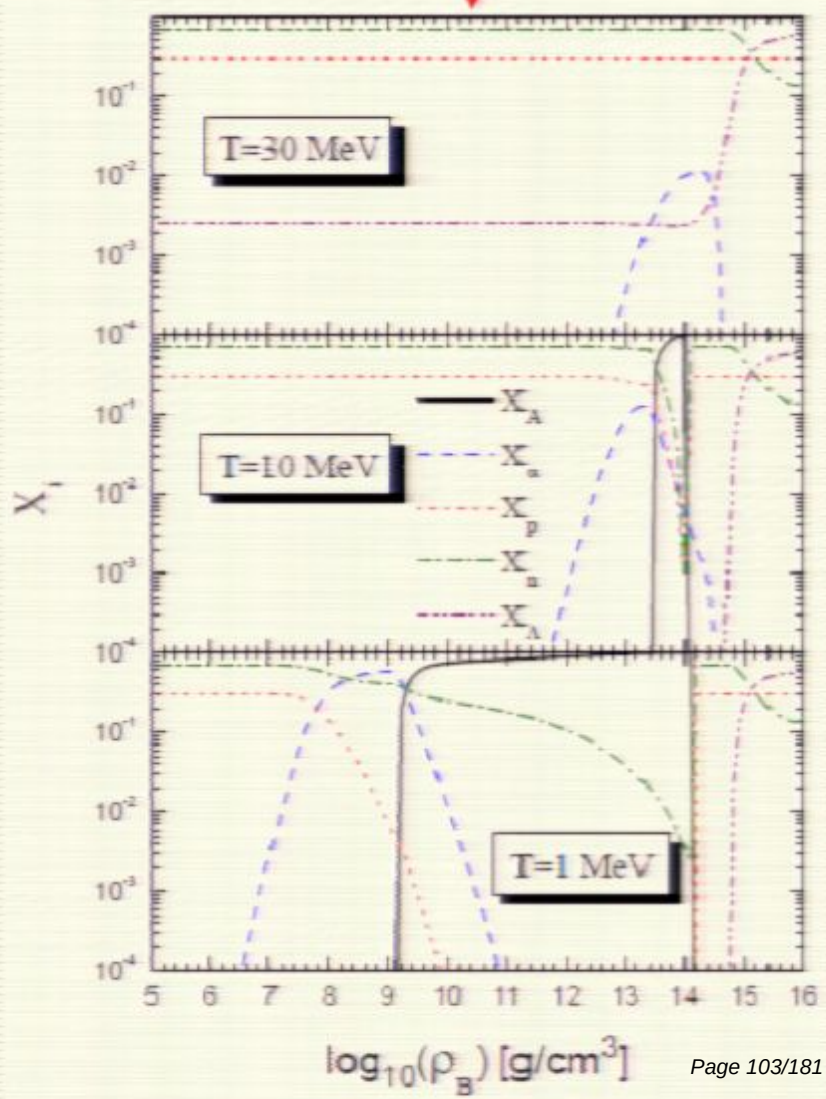




Fractions of components

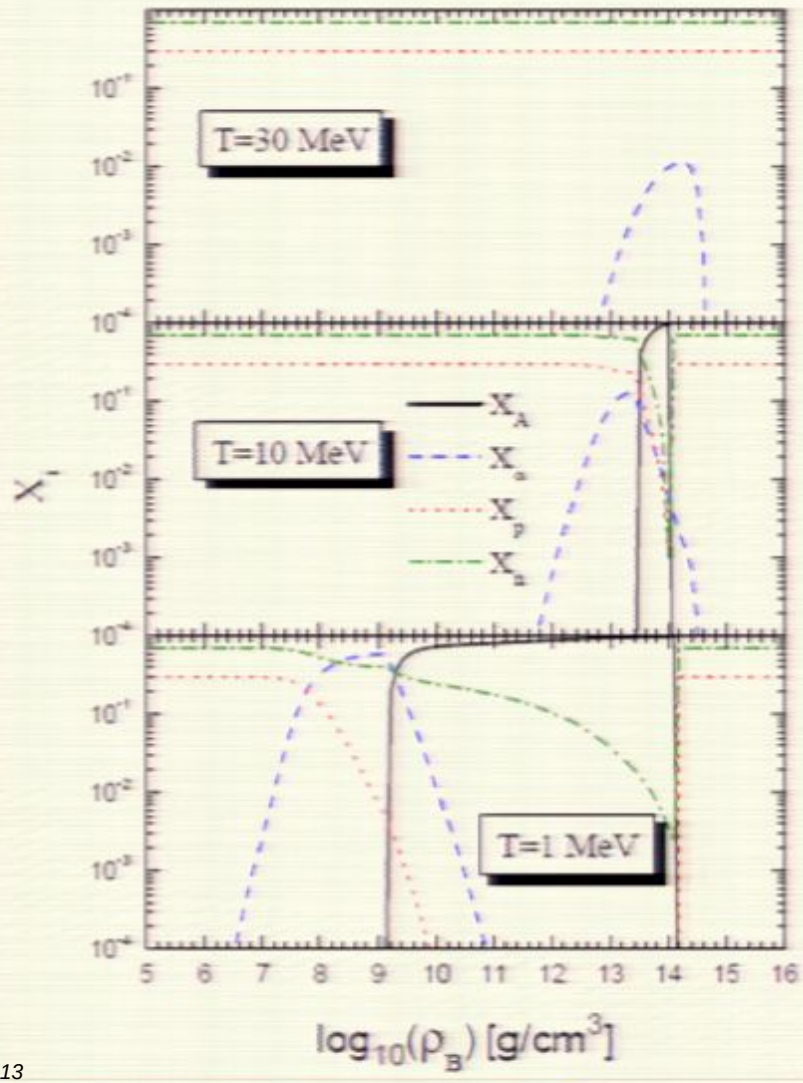
with Λ hyperons

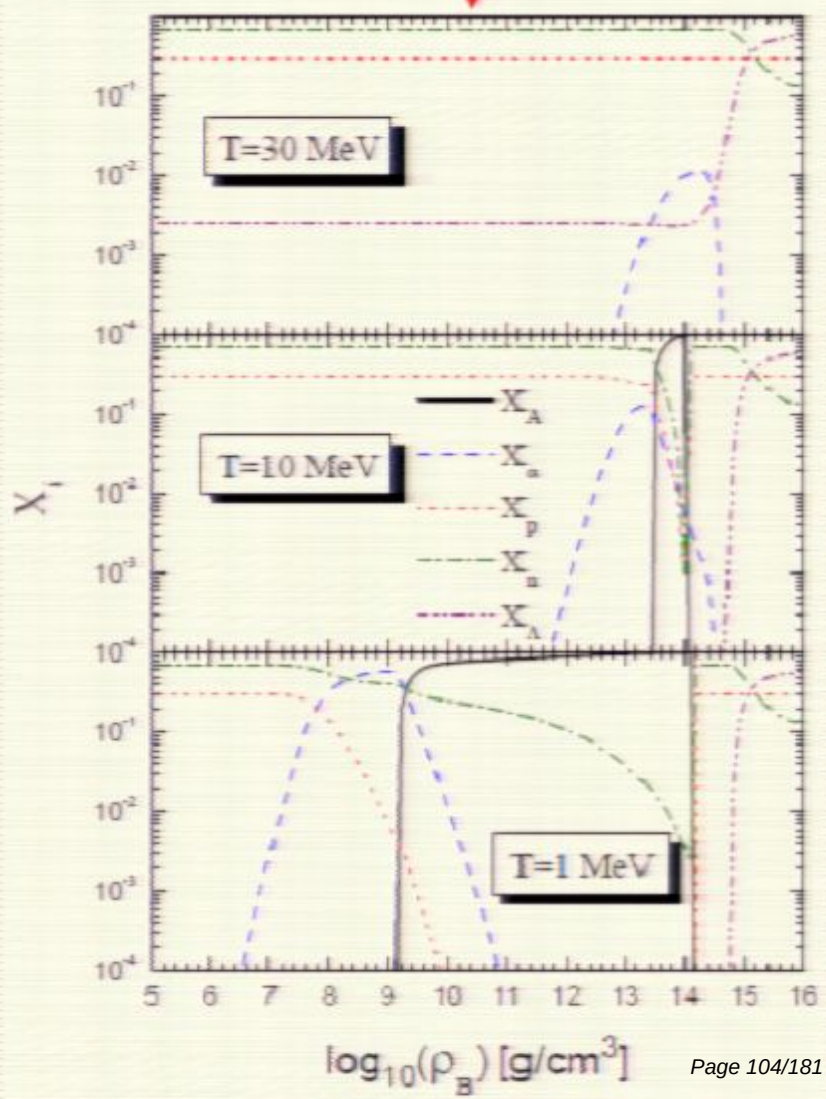




Fractions of components

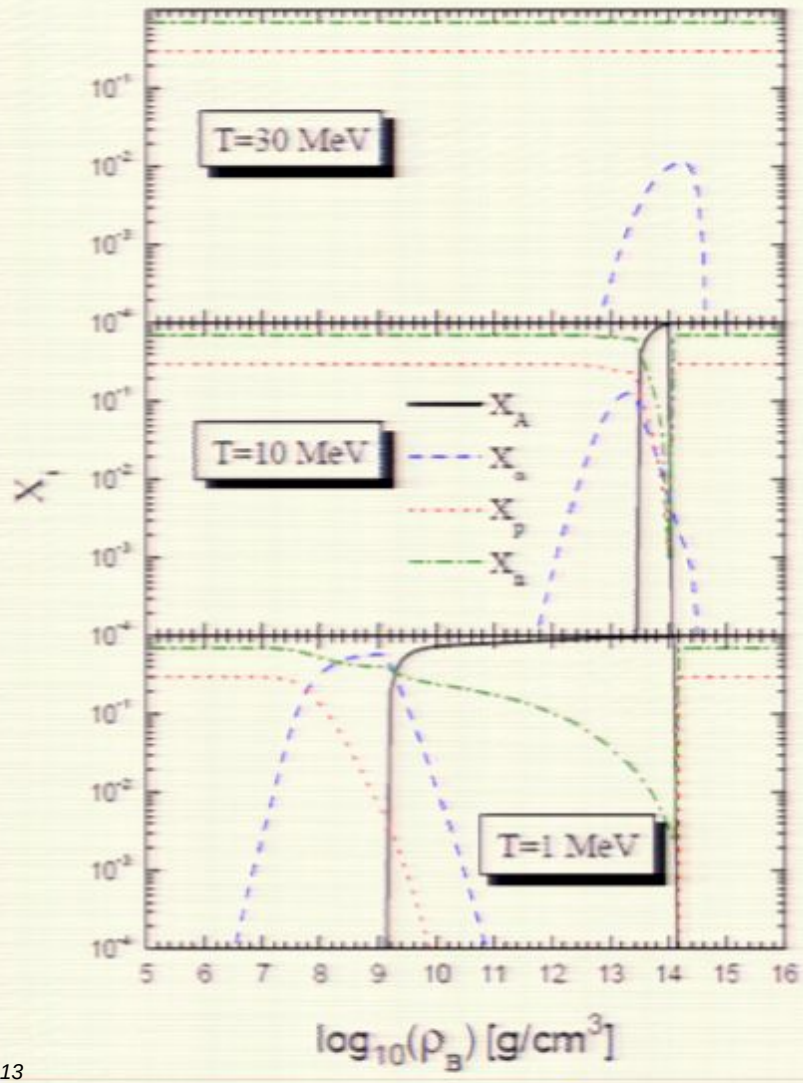
with Λ hyperons

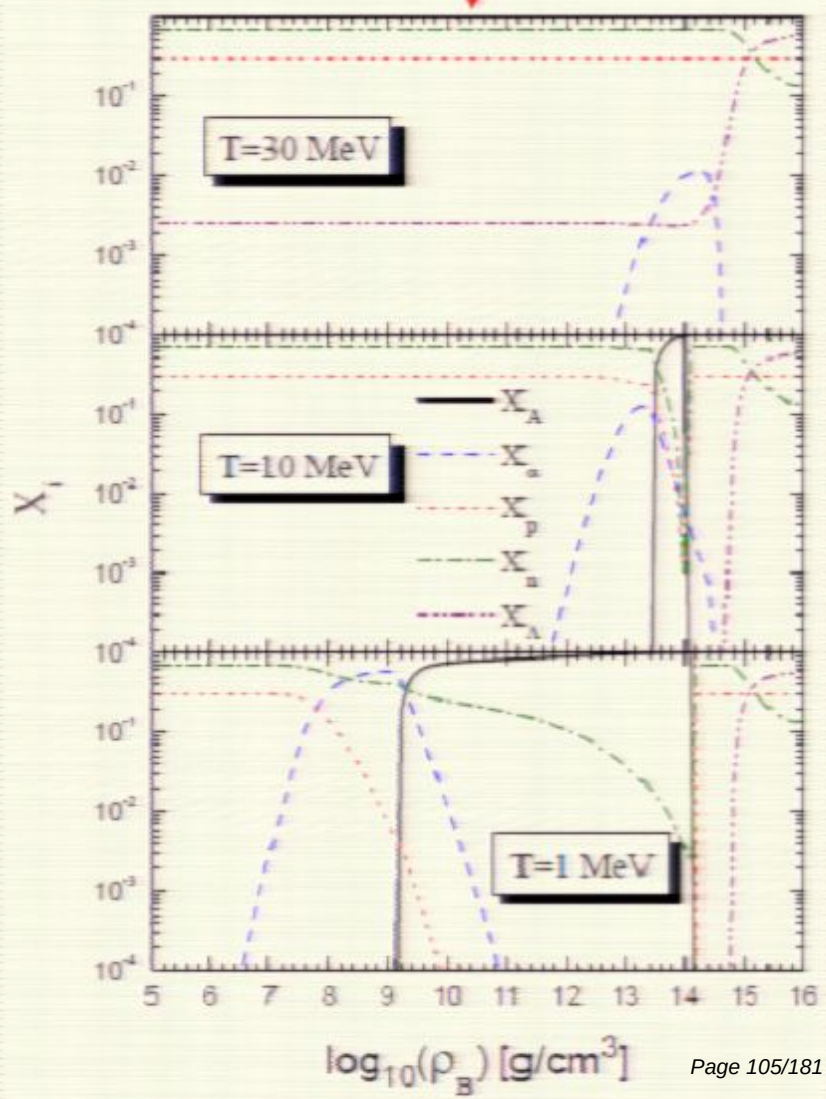




Fractions of components

with Λ hyperons





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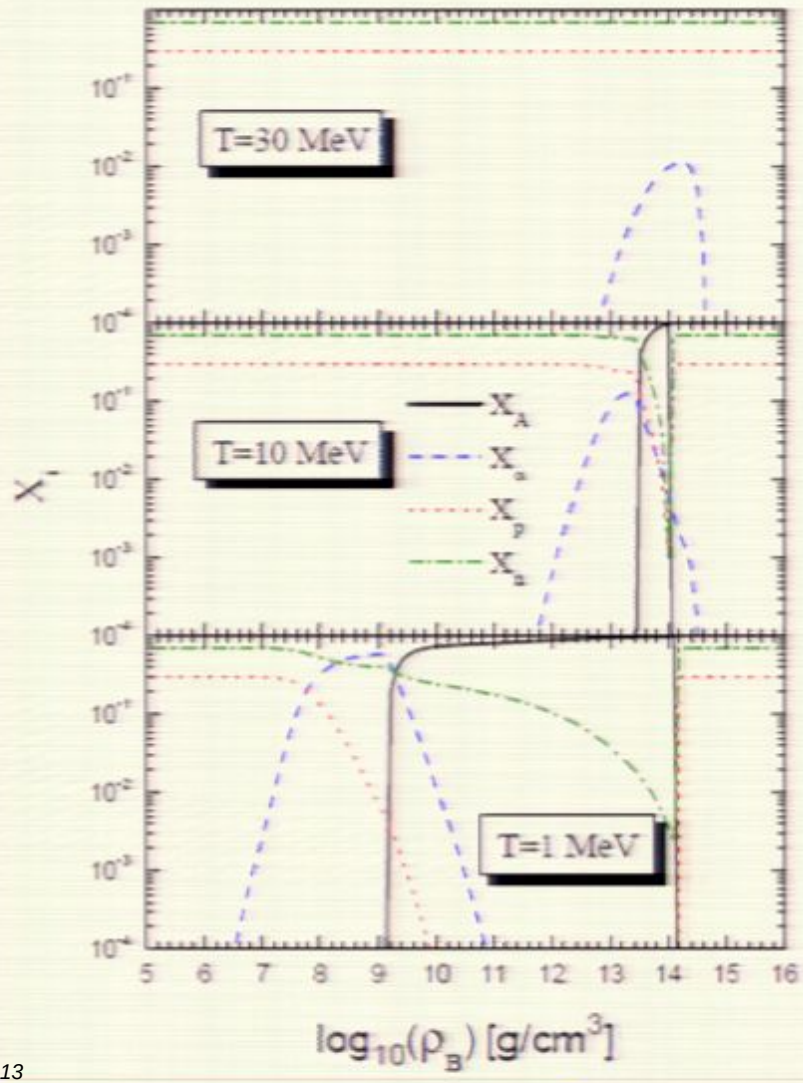

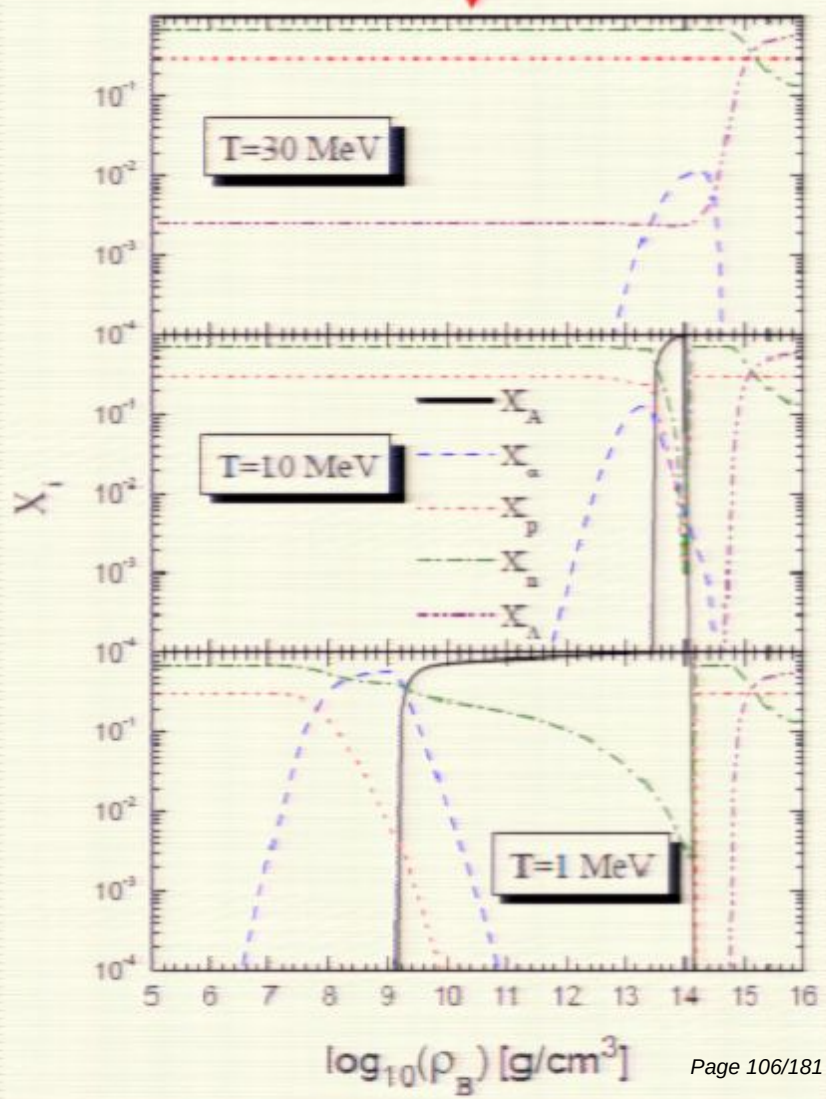

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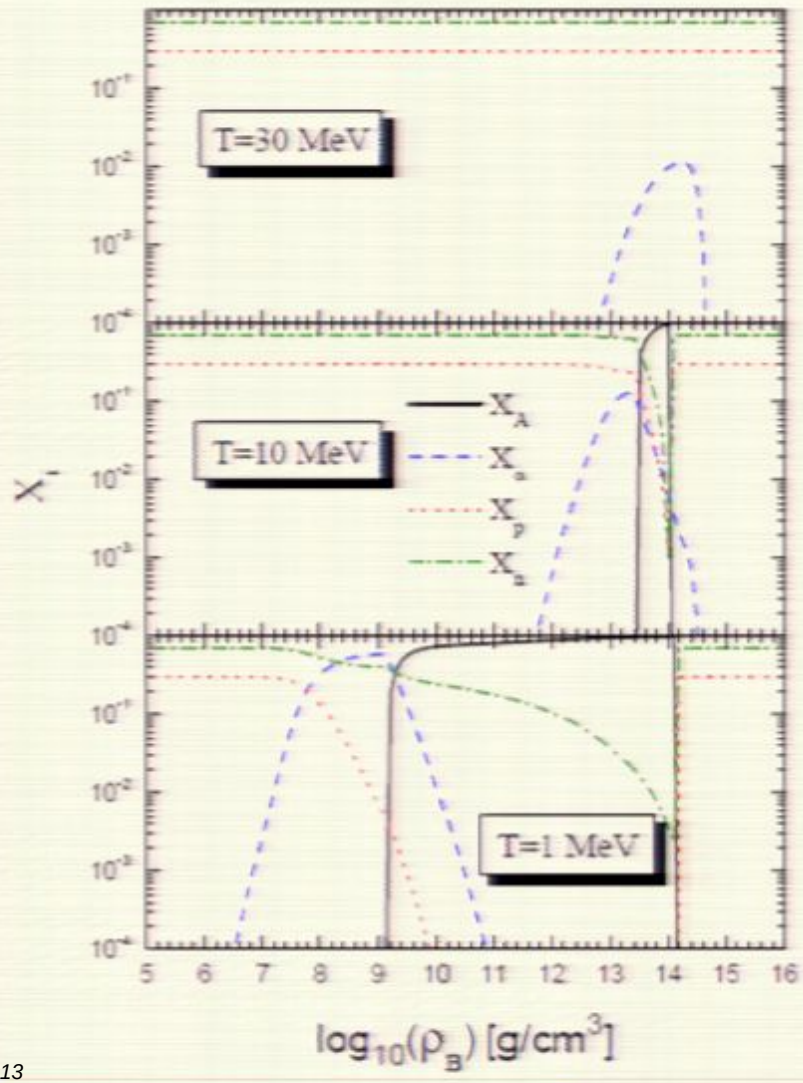

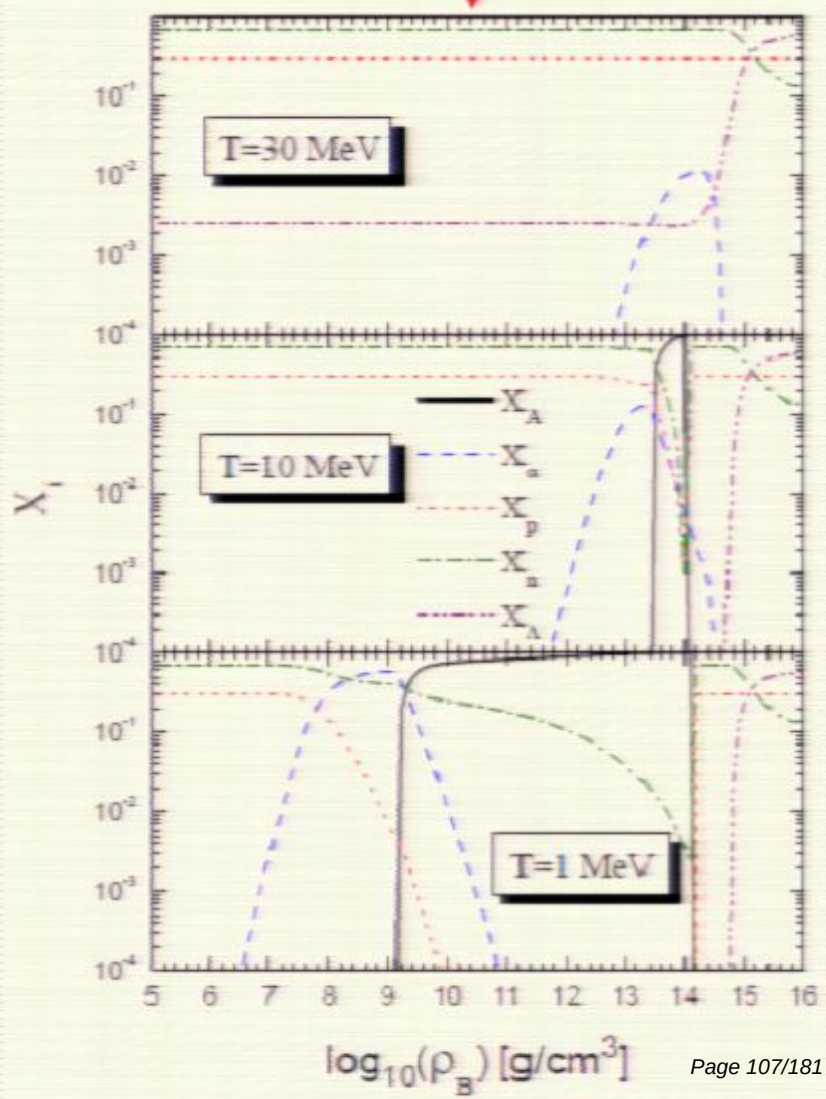

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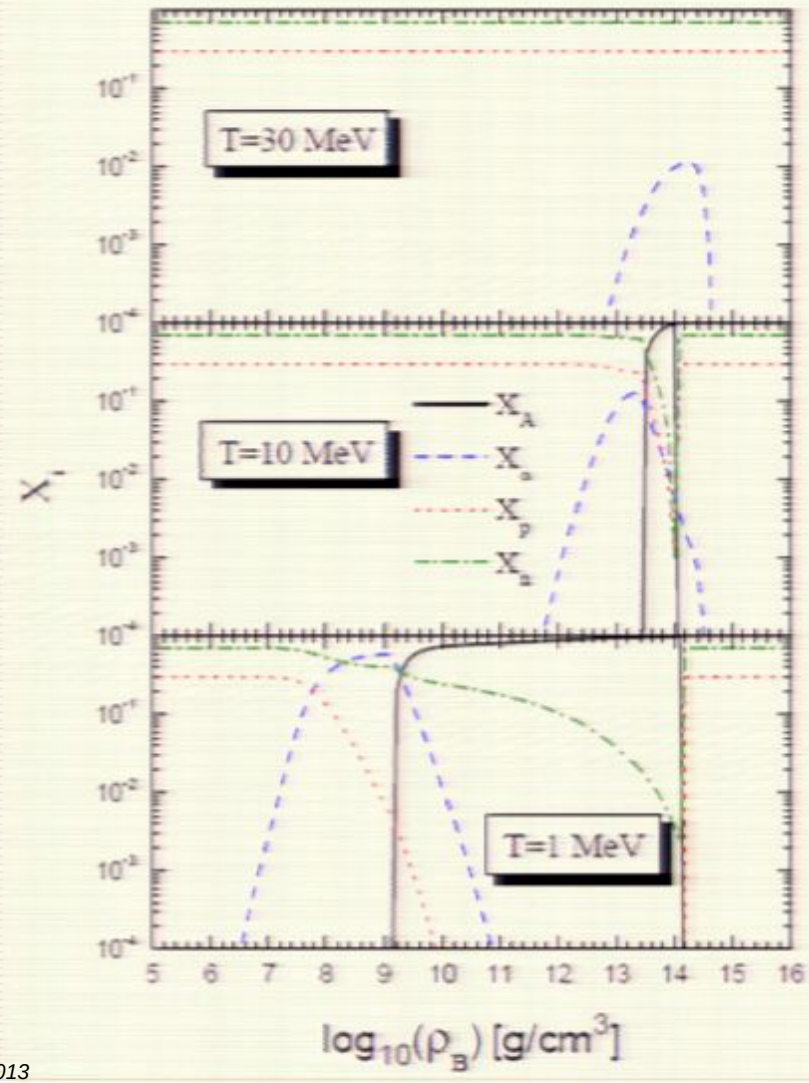

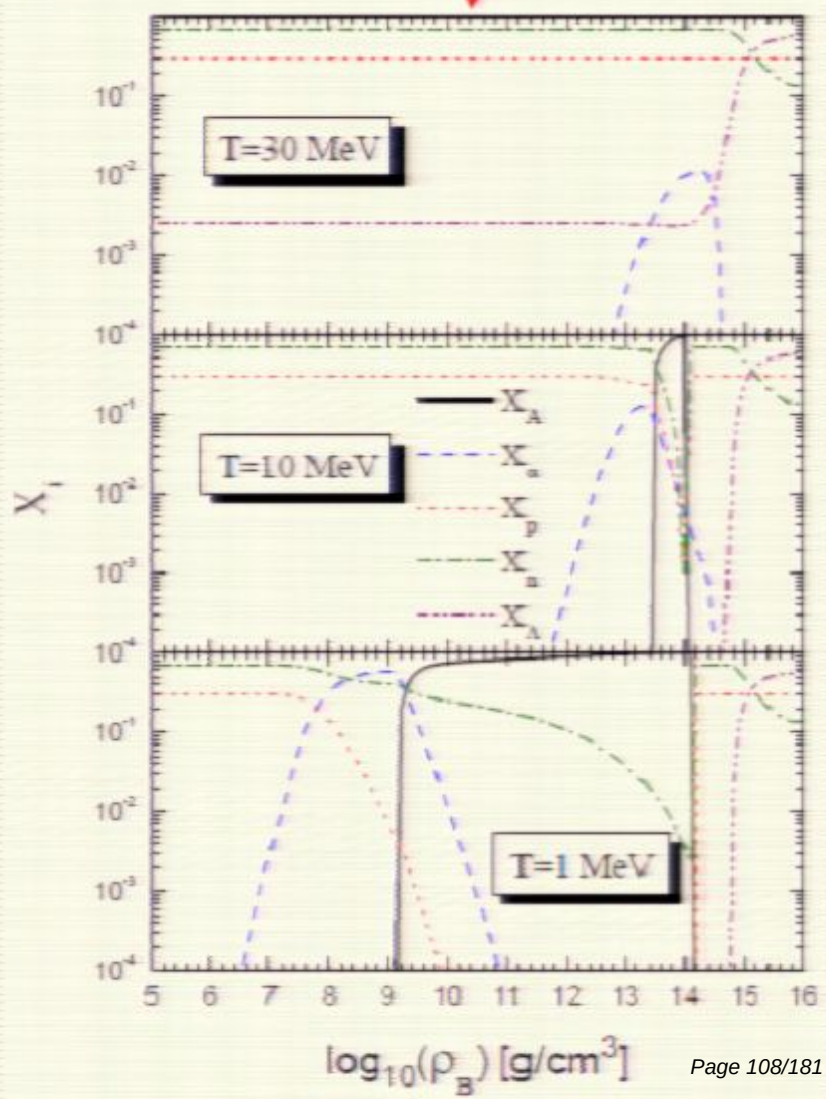

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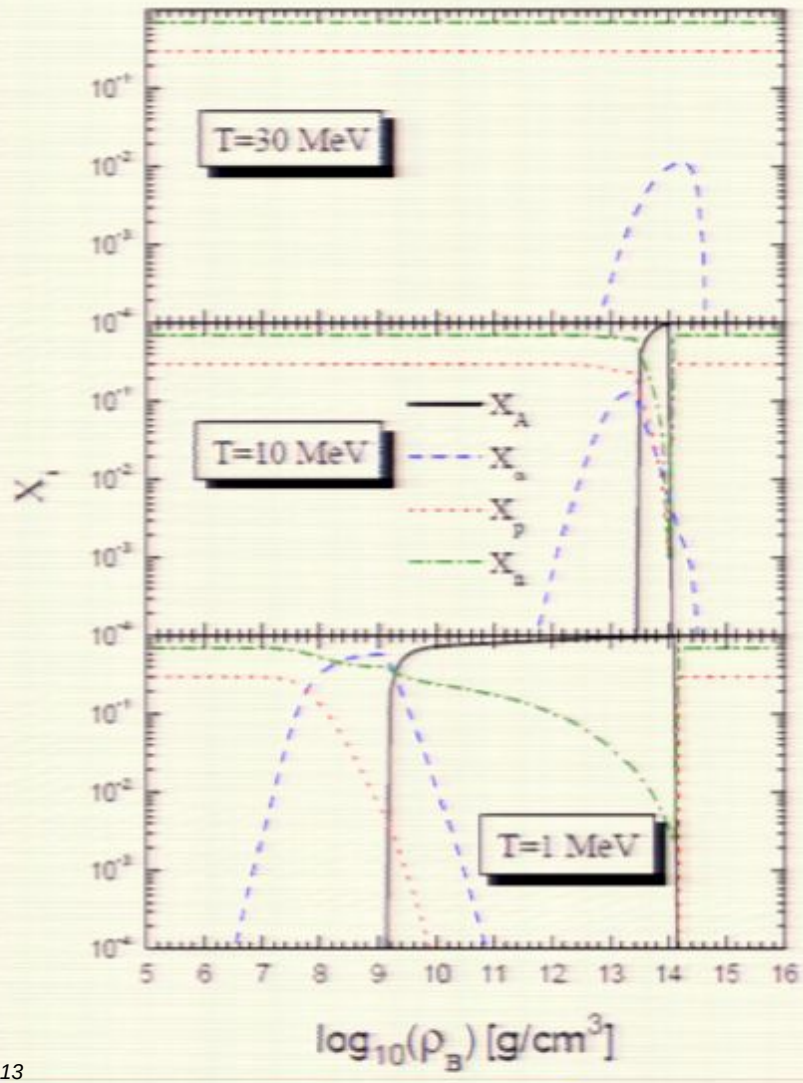

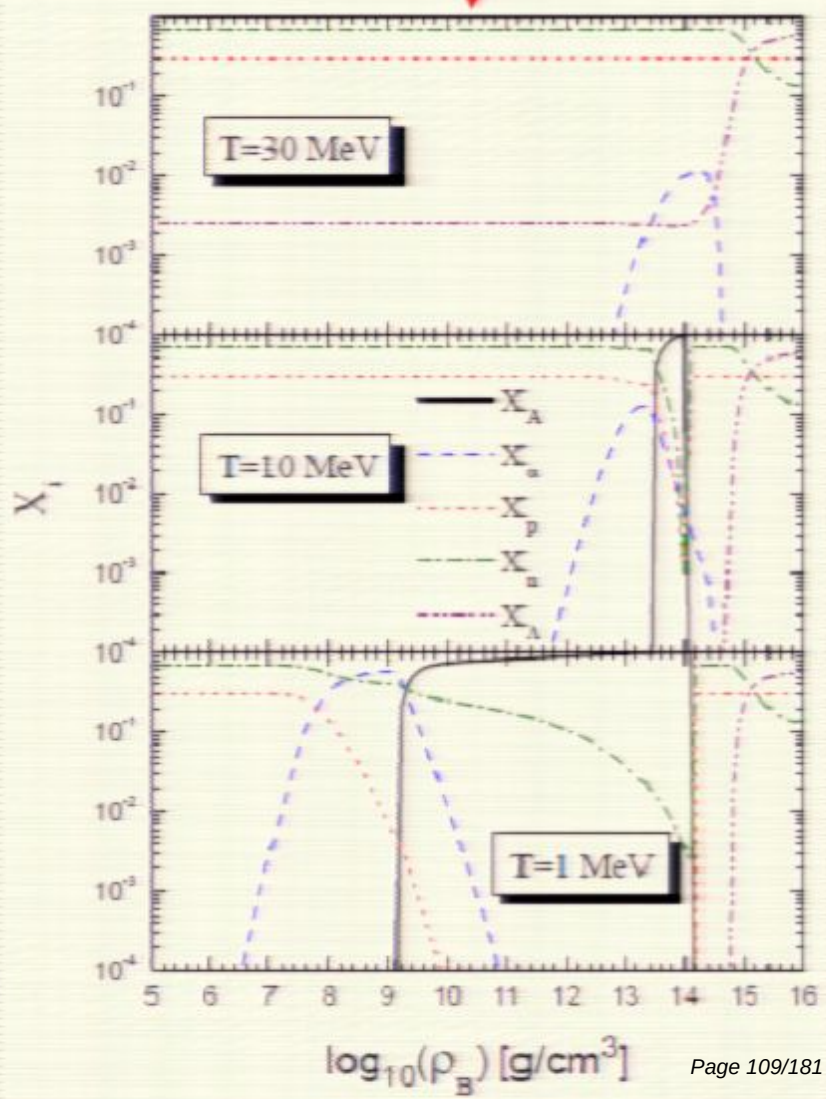

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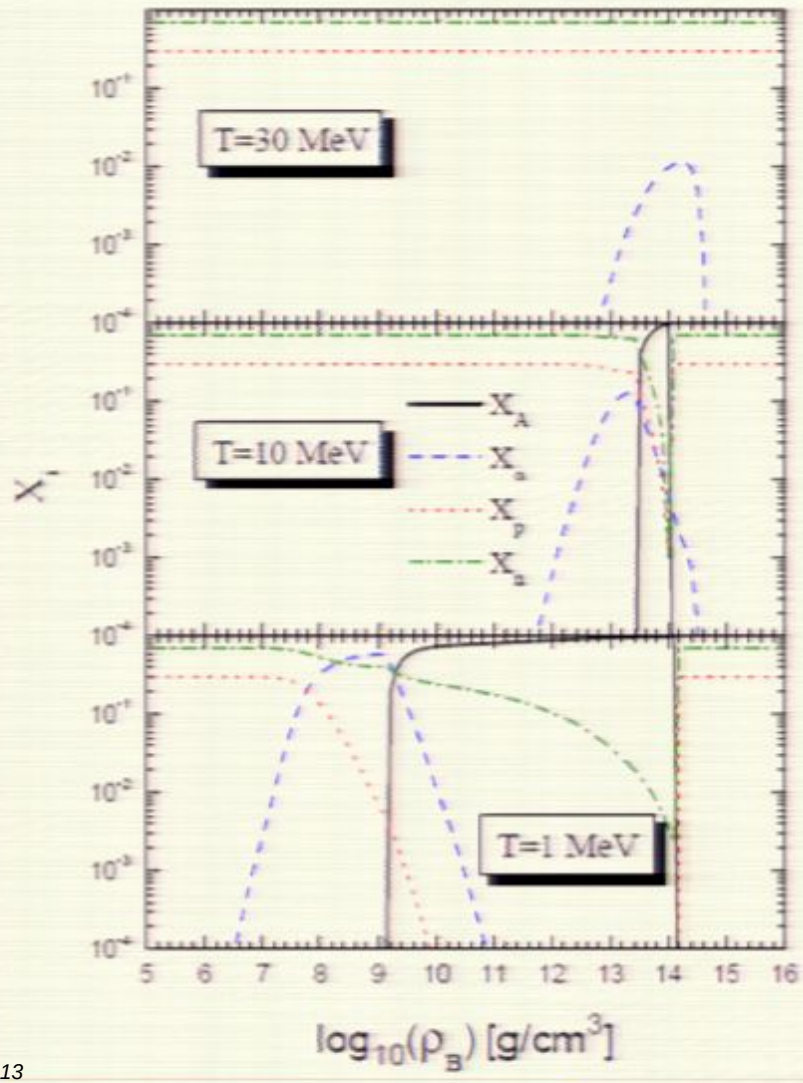

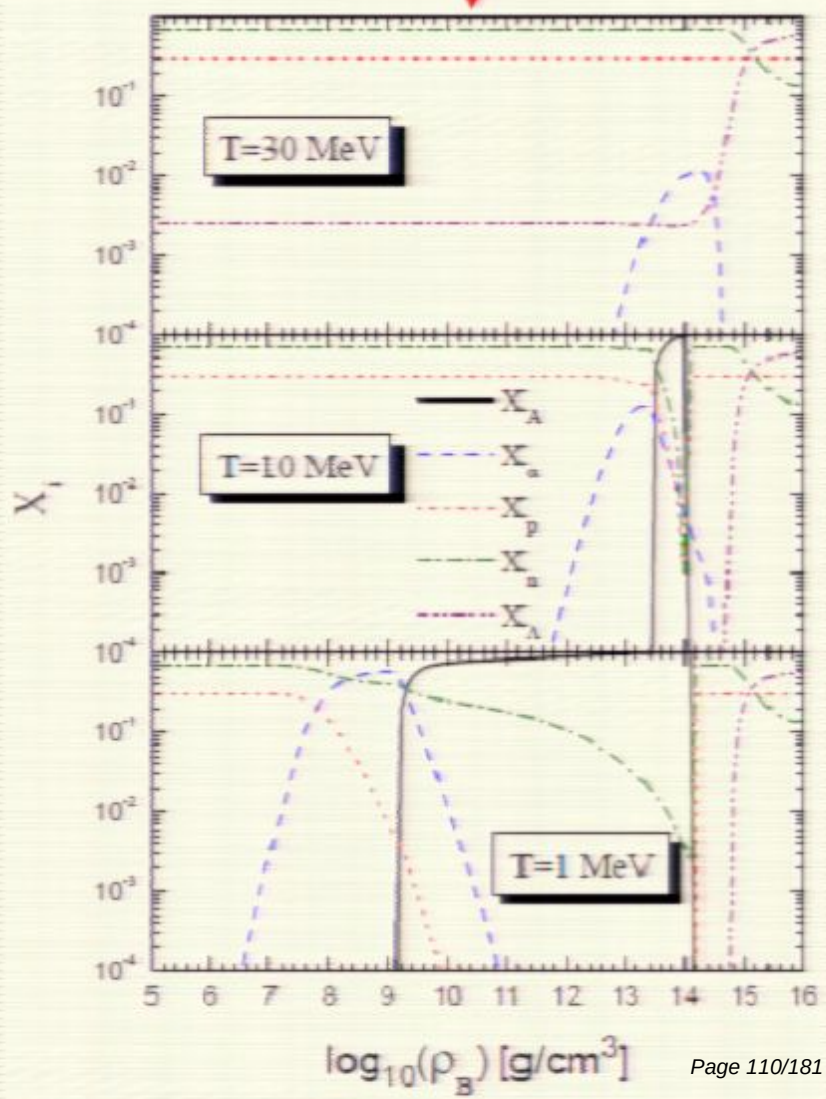

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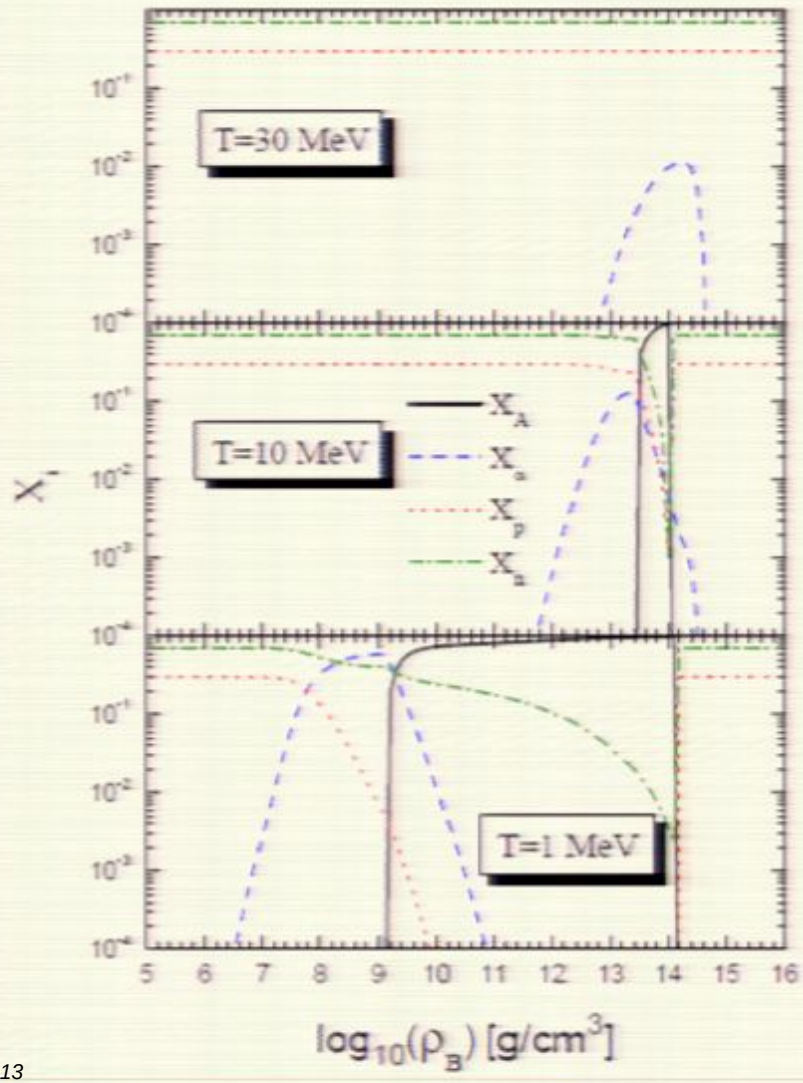

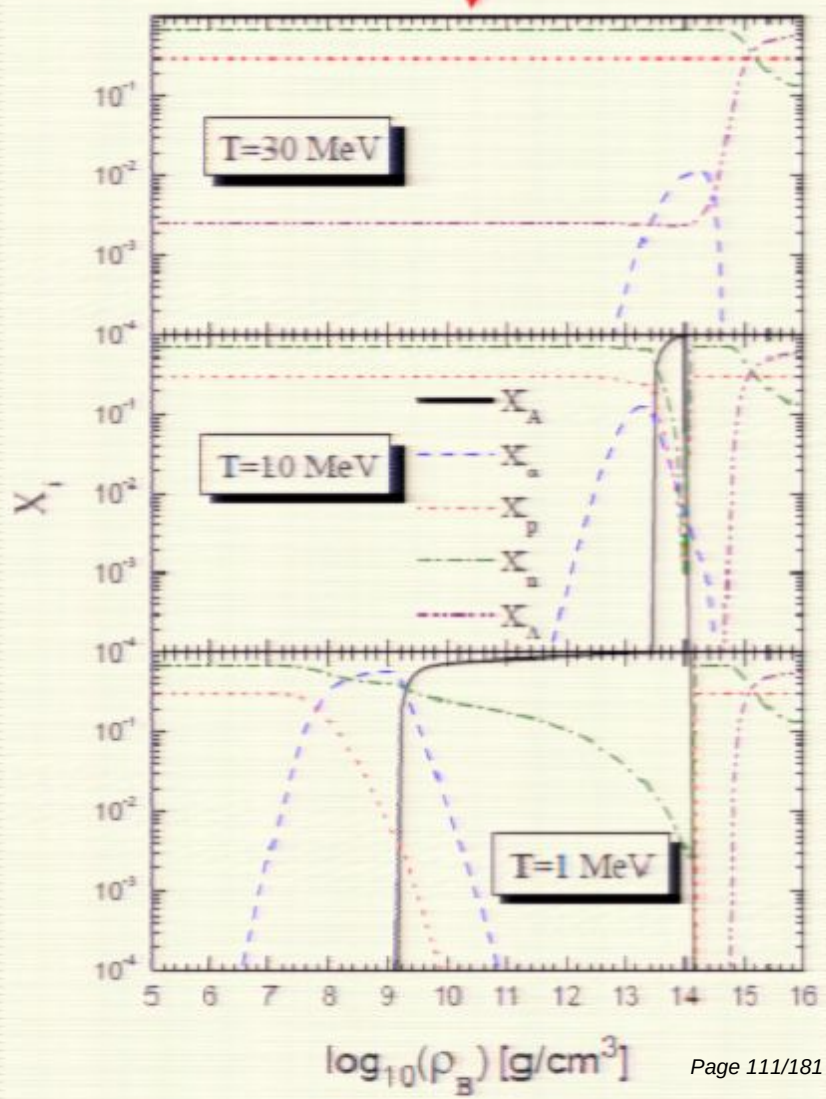

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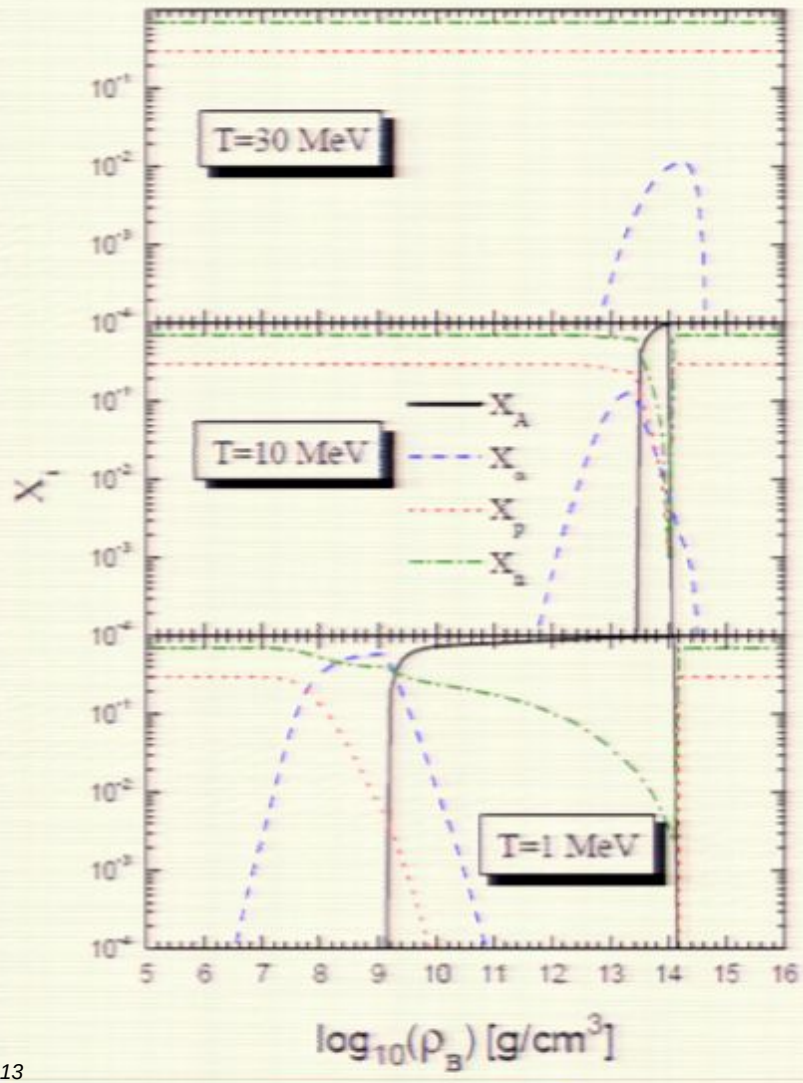

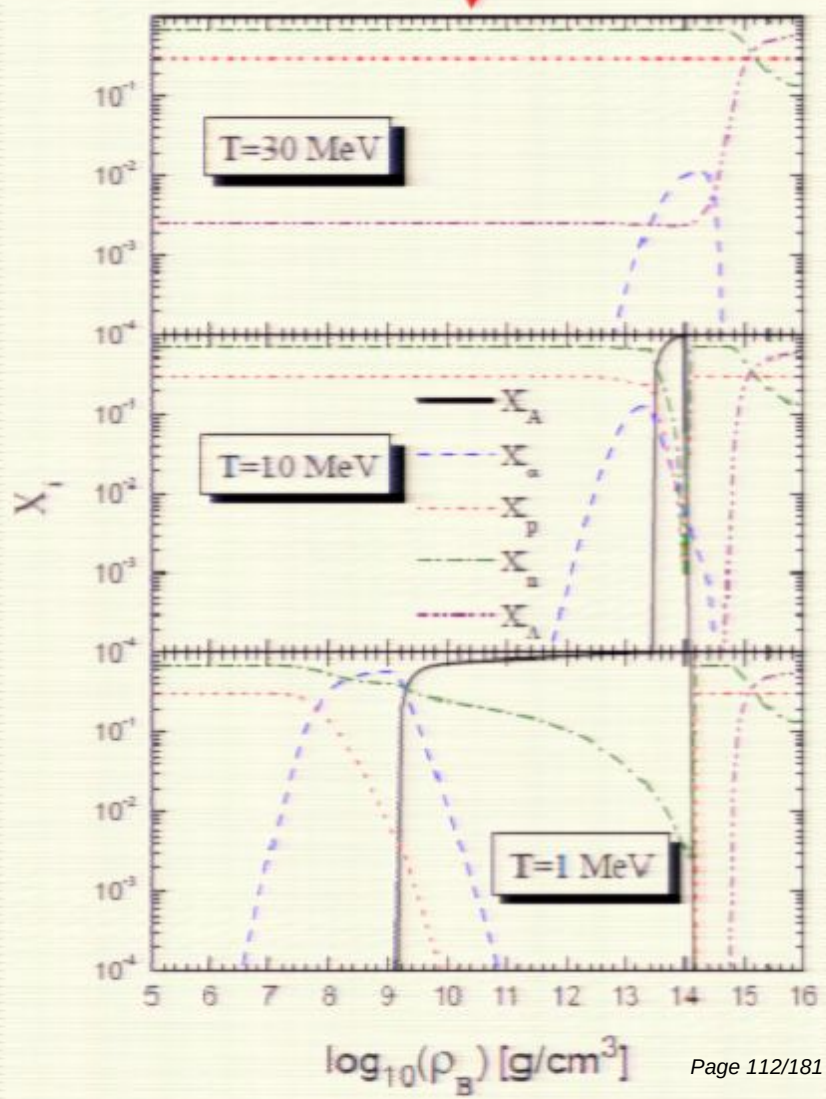

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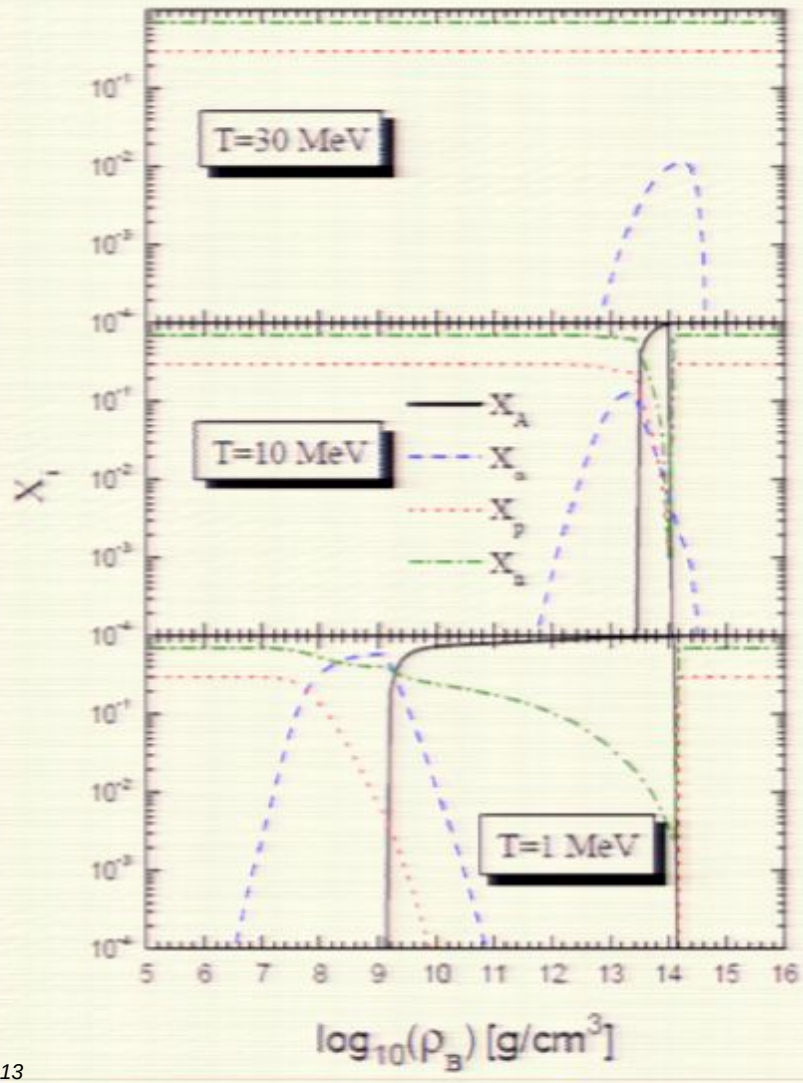

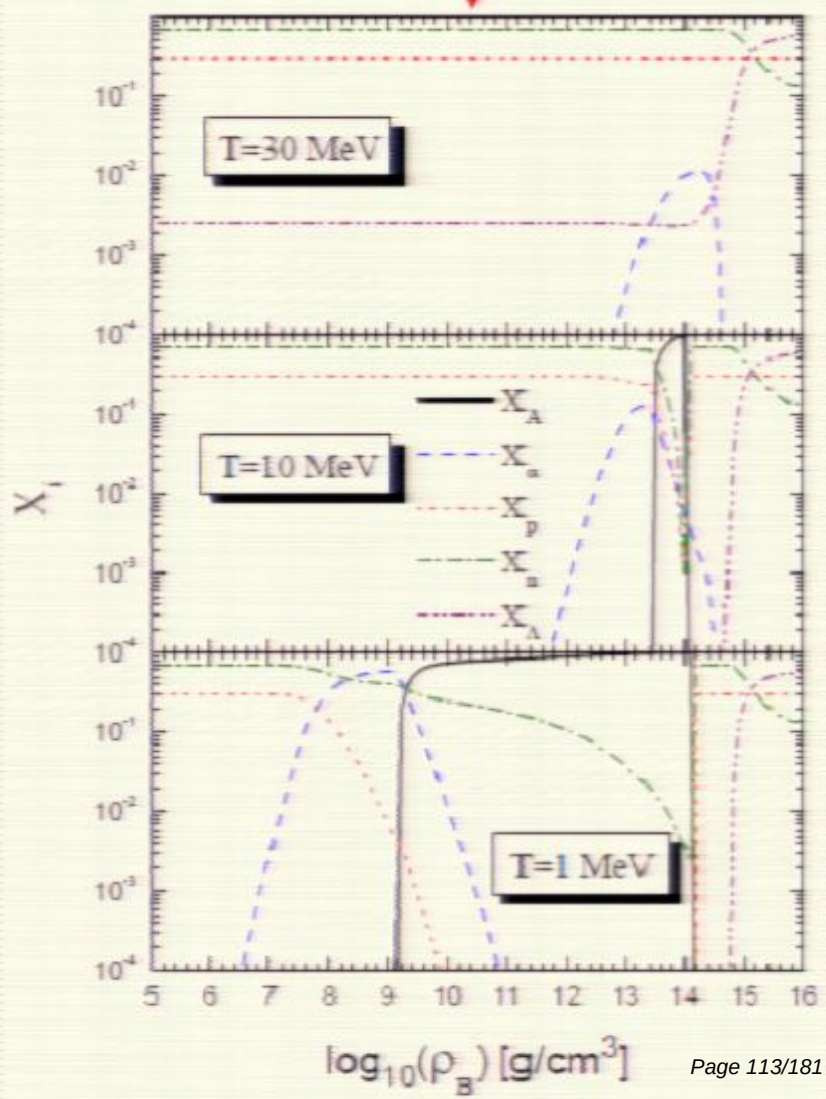

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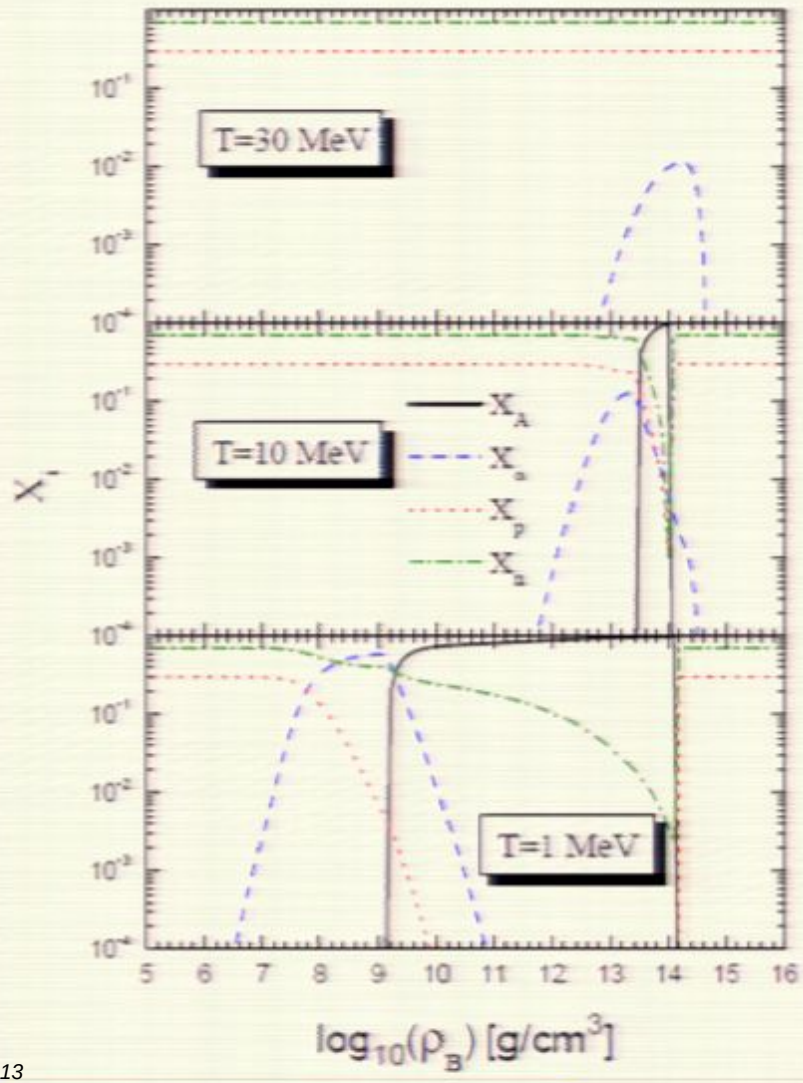

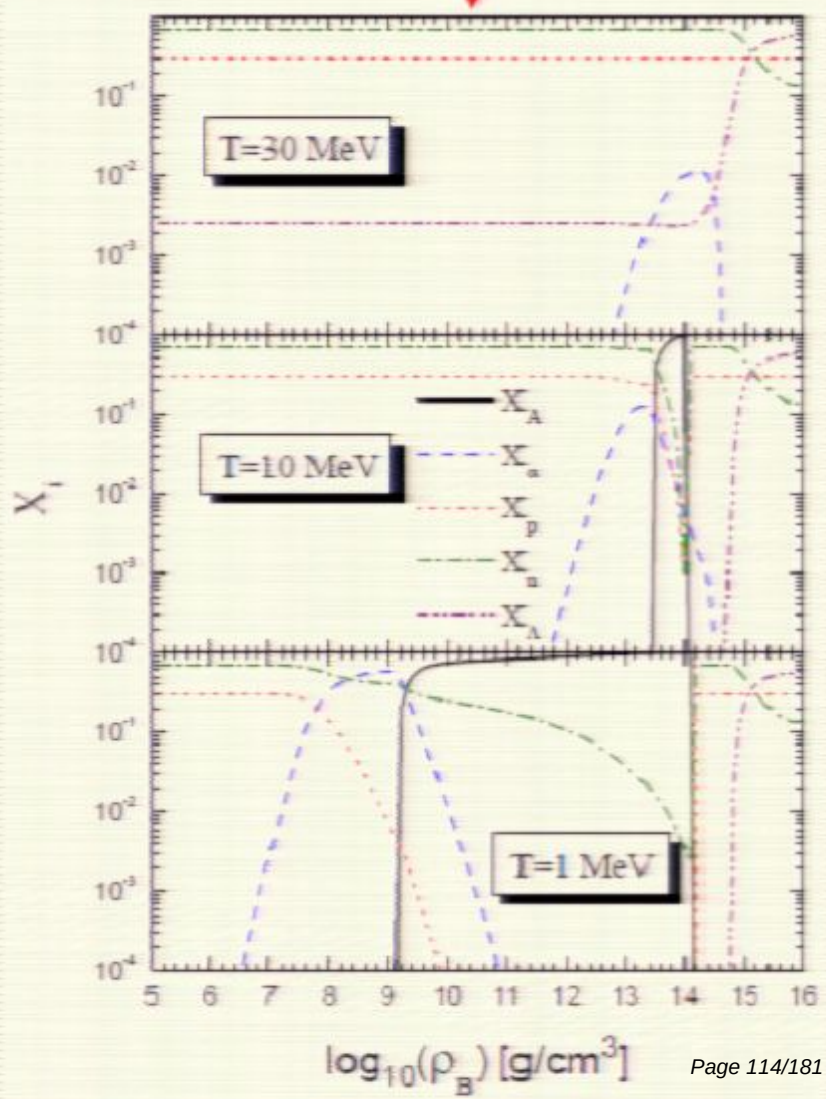

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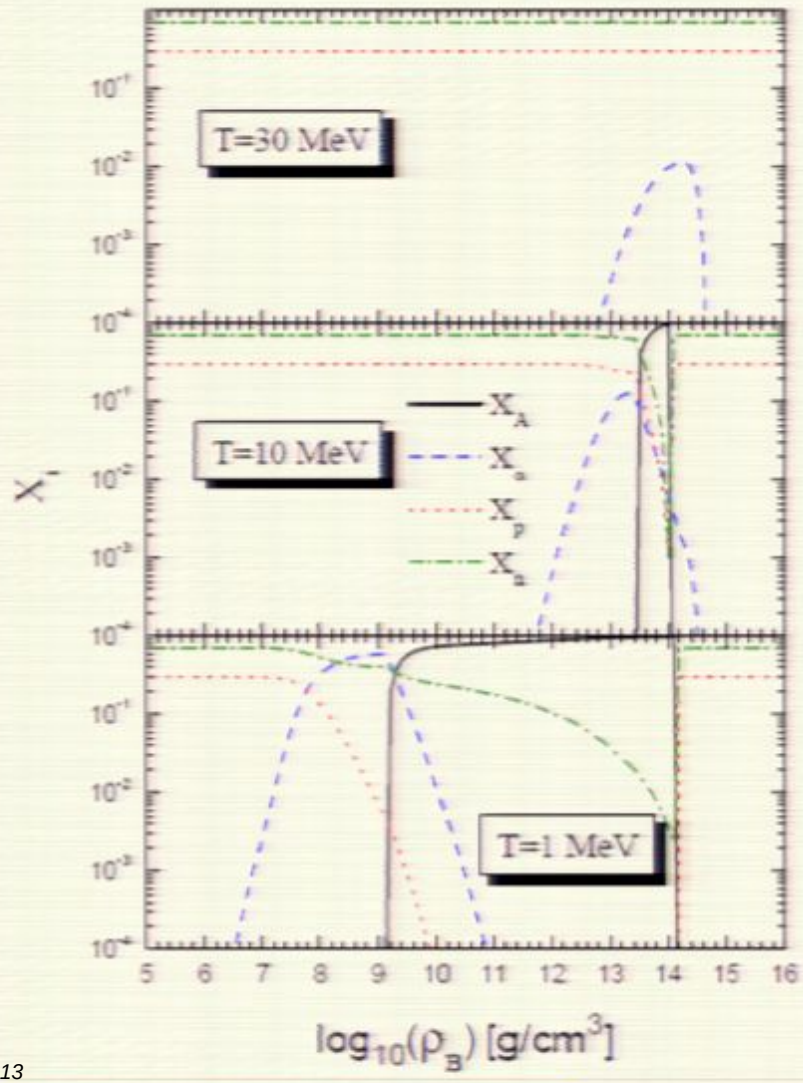

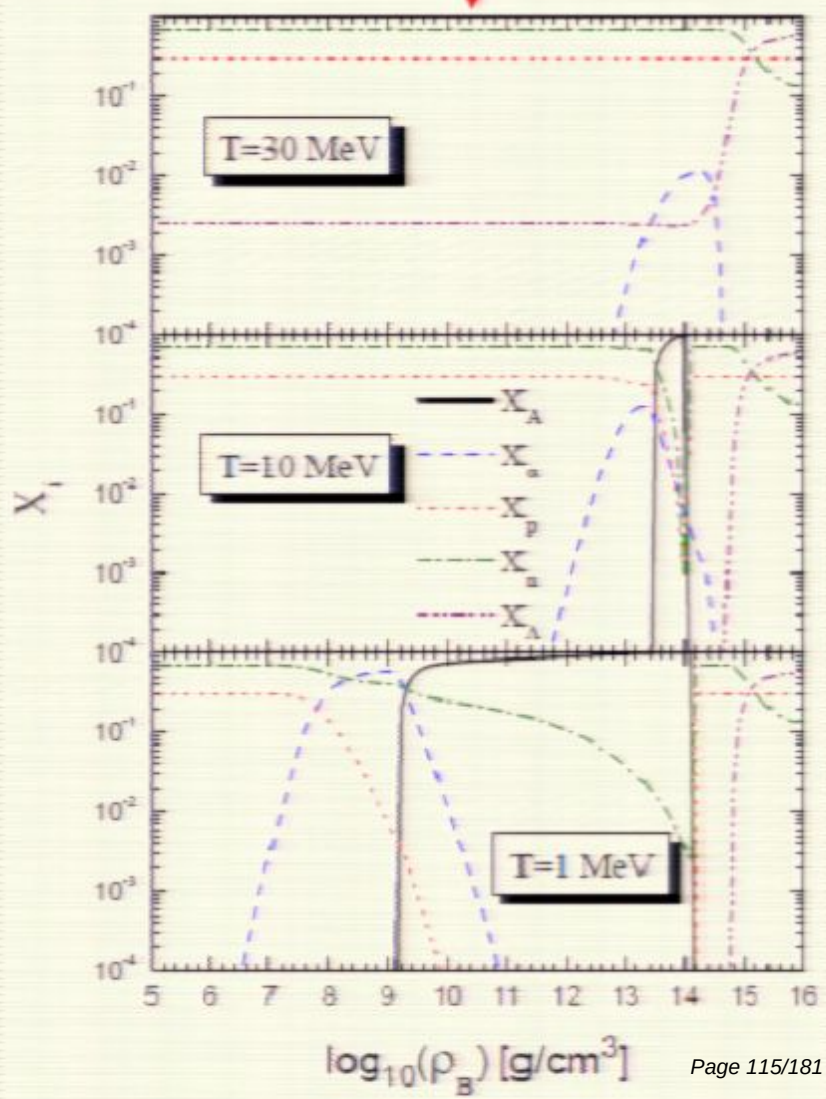

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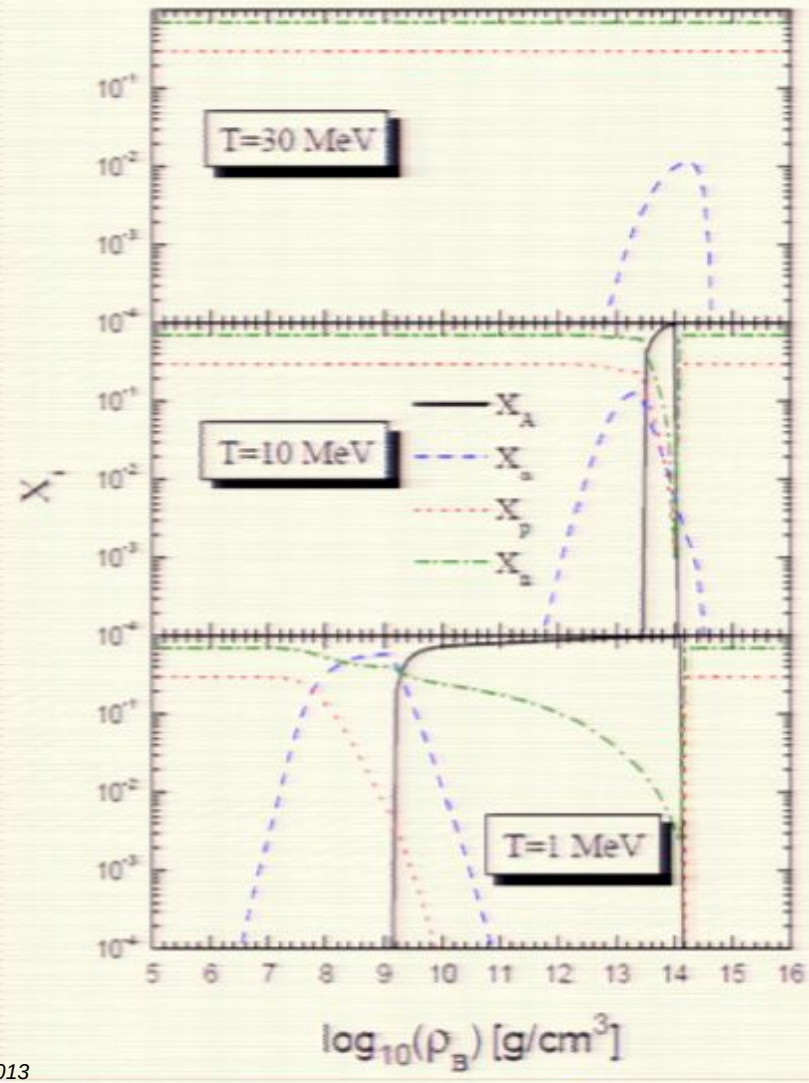

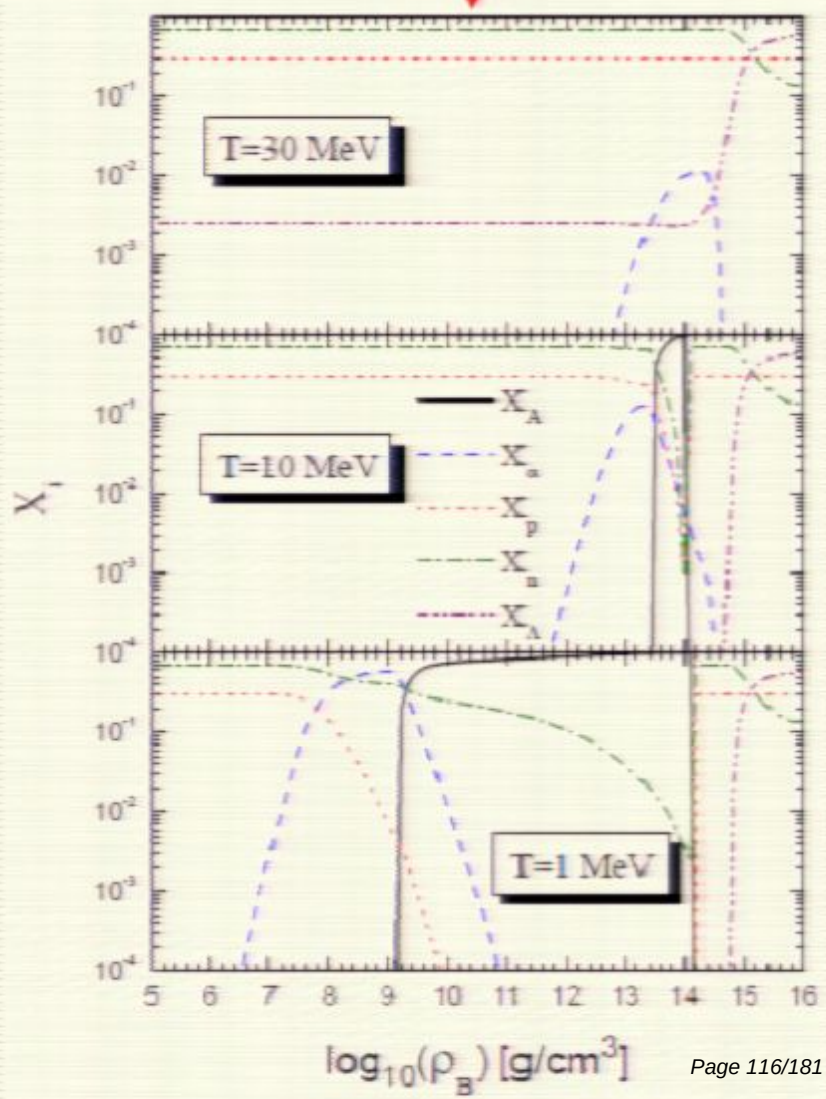

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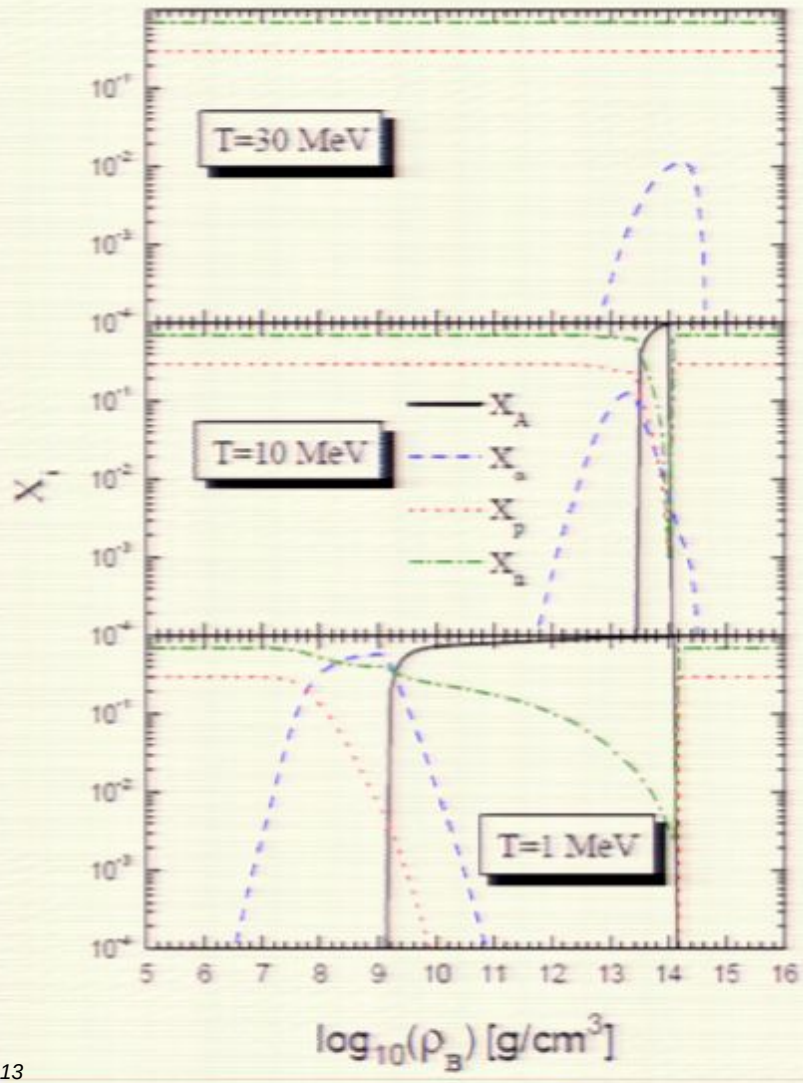

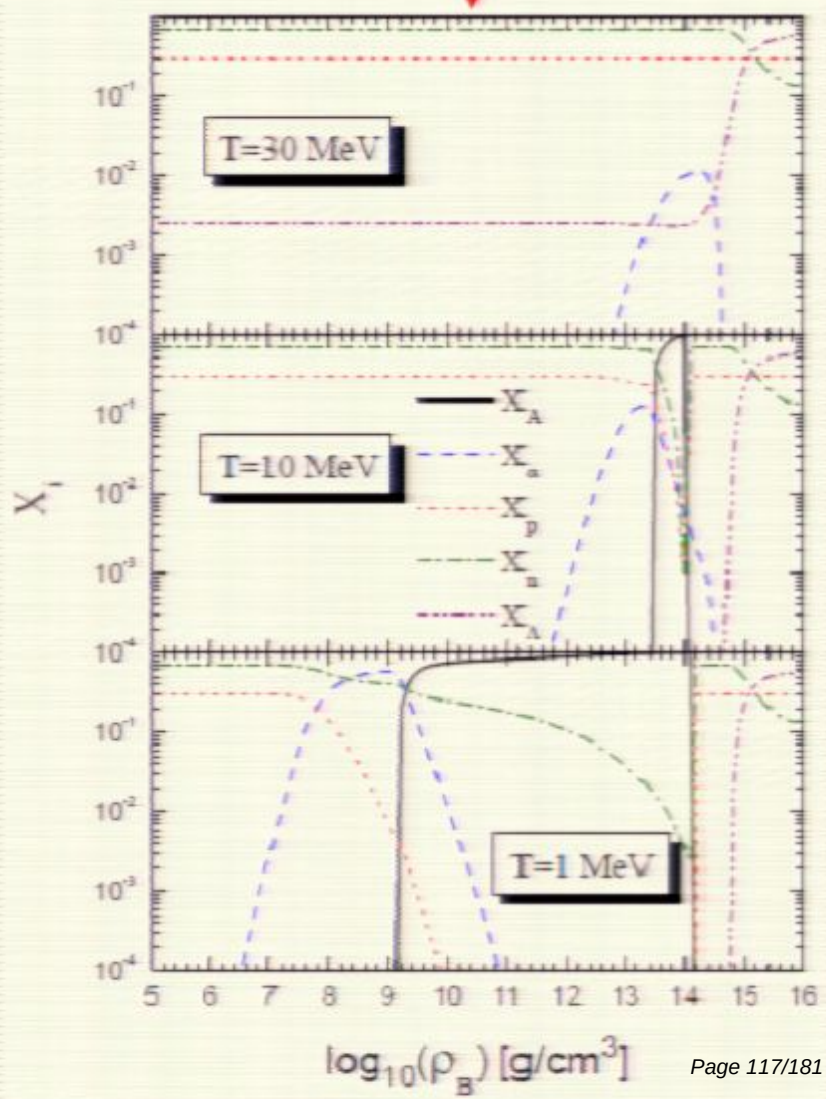

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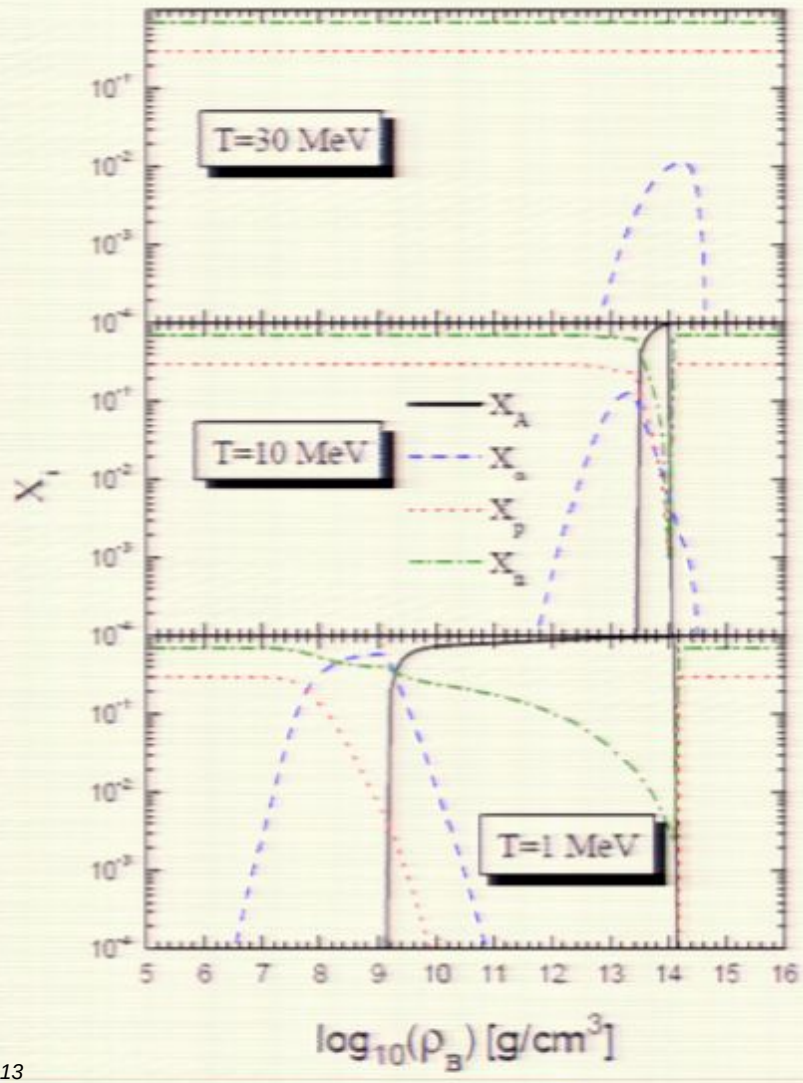

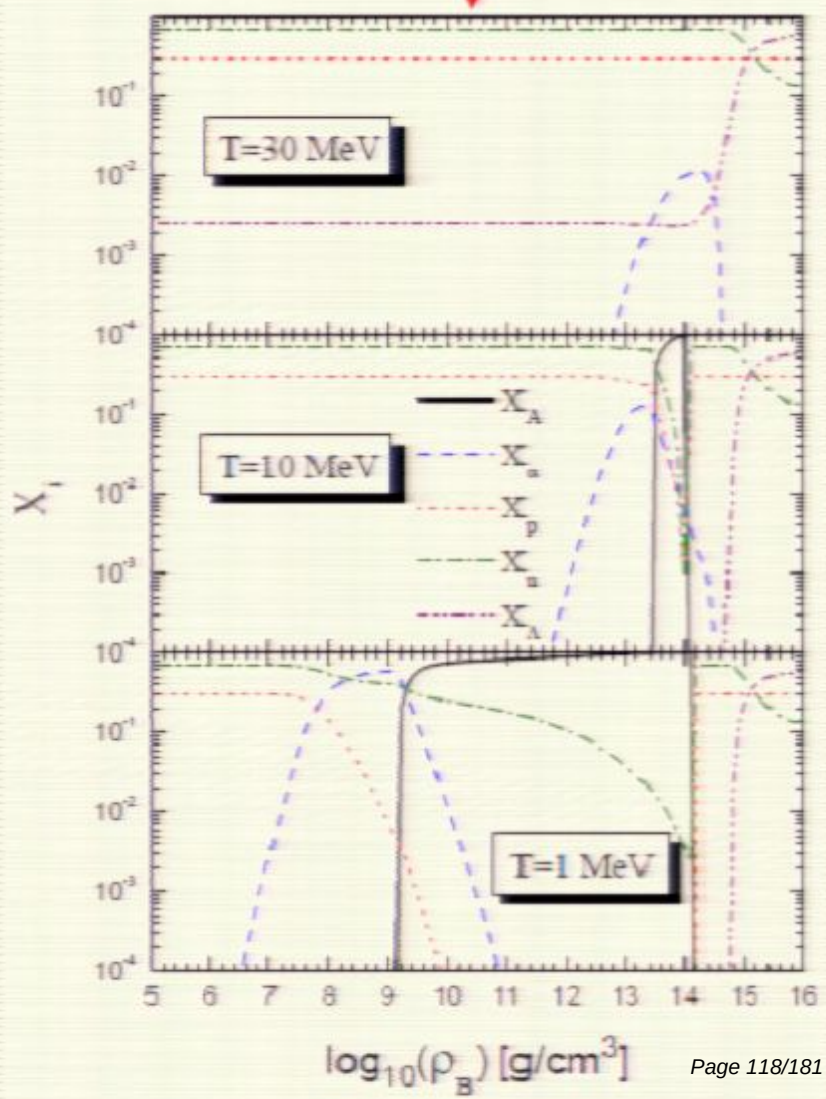

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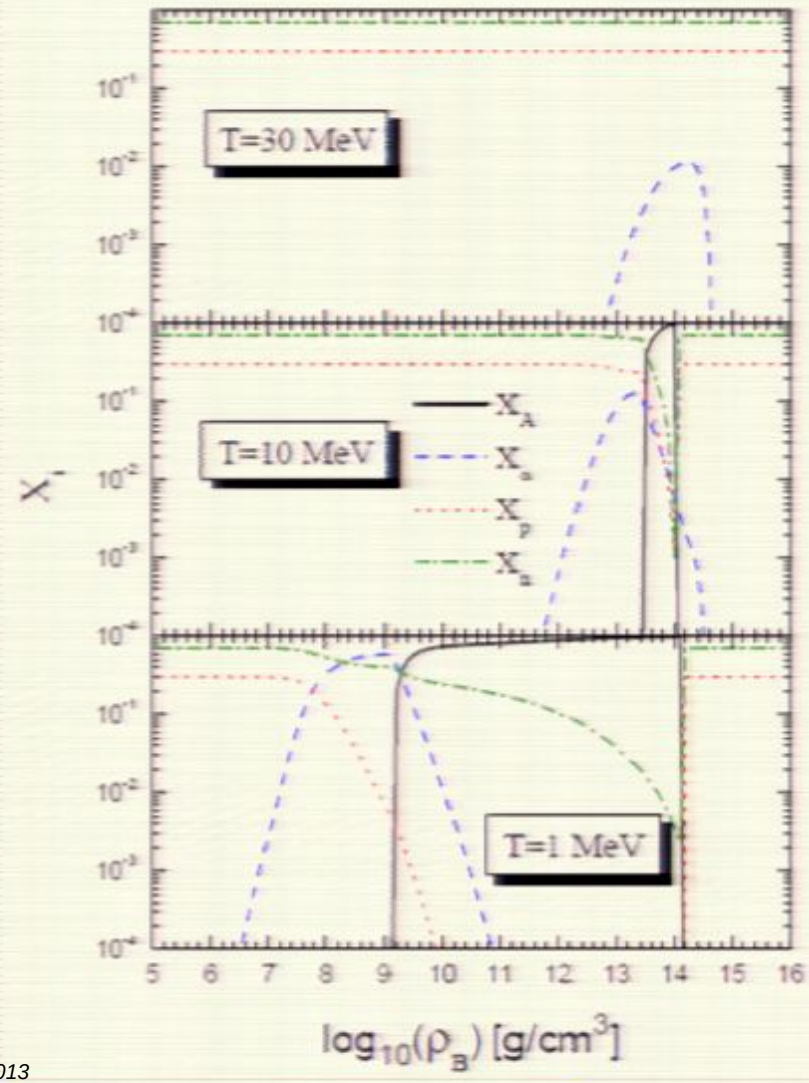

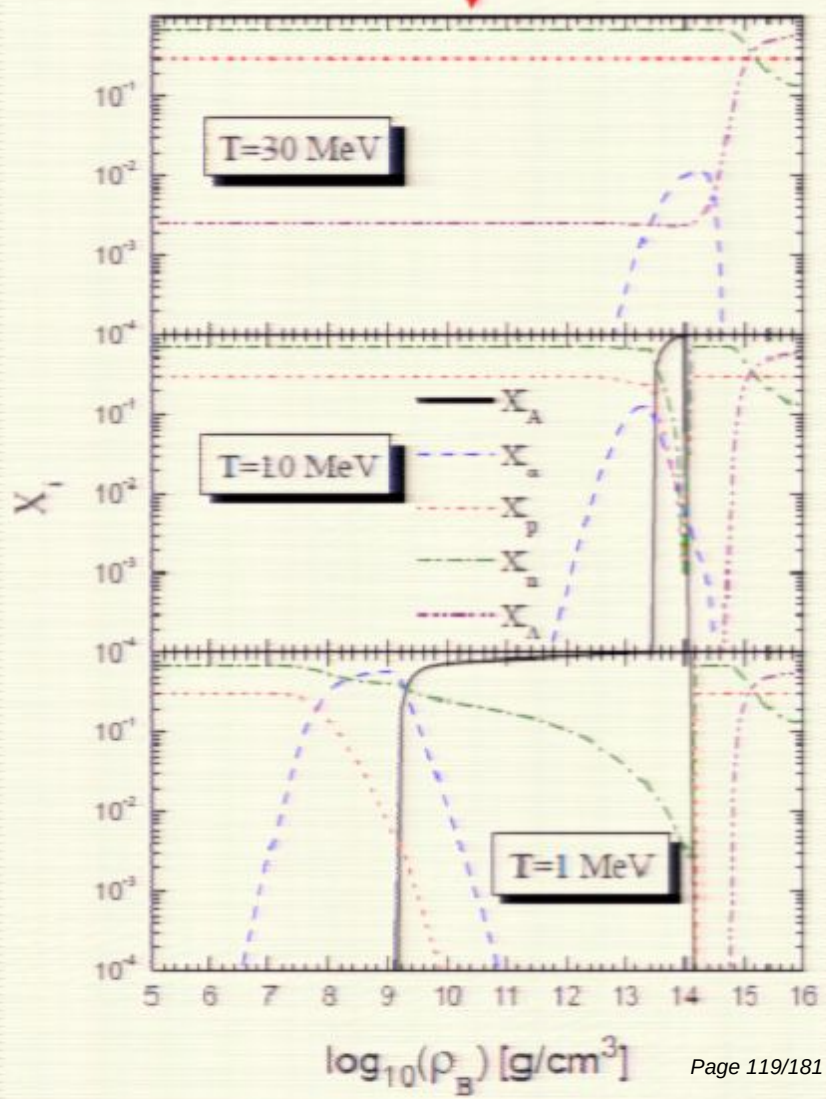

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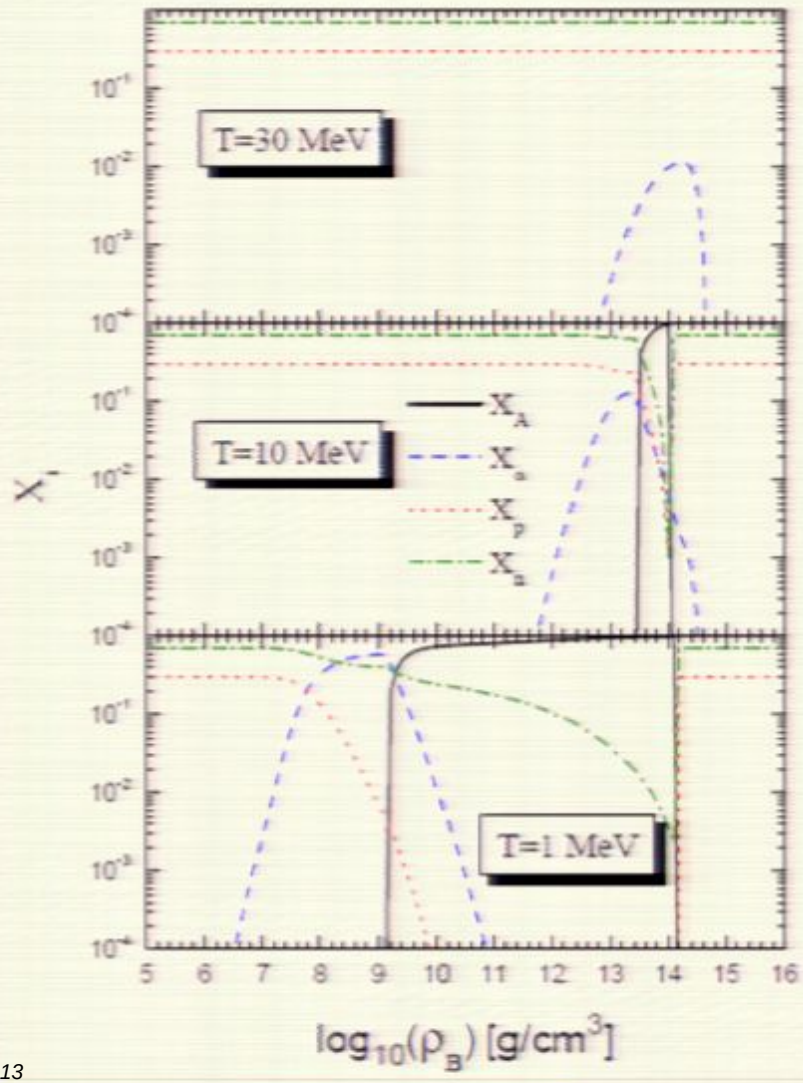

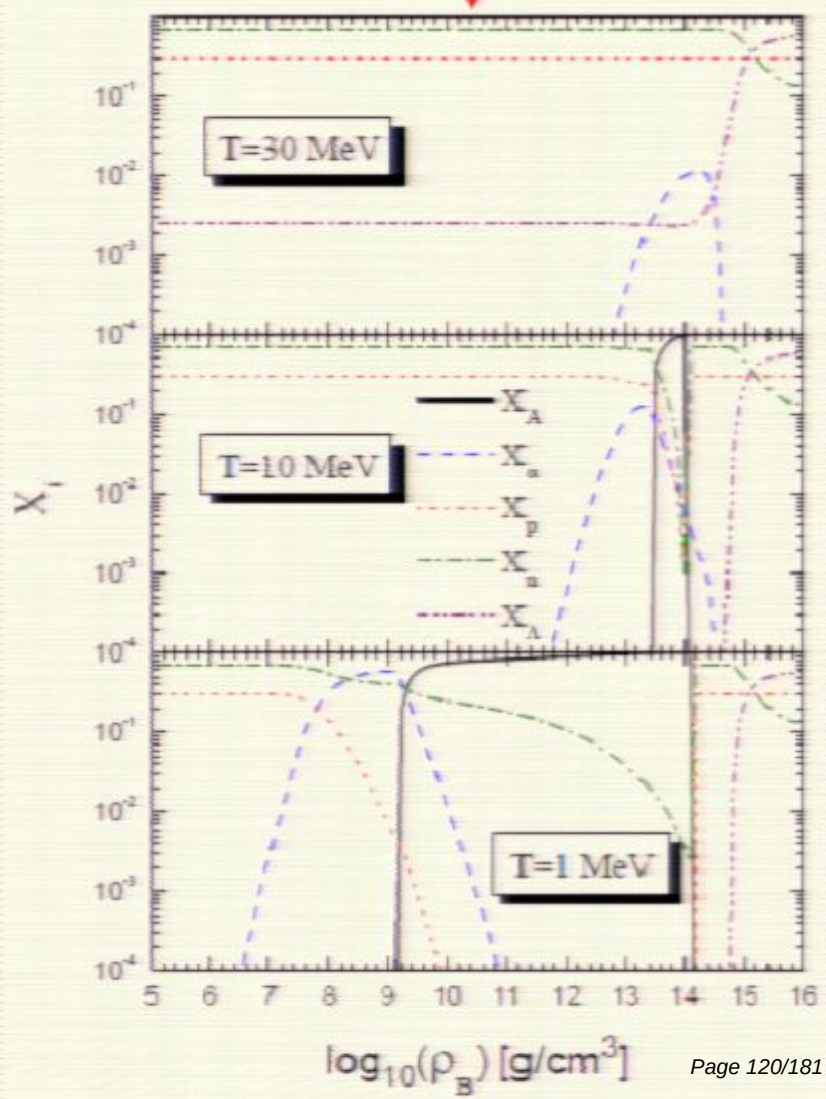

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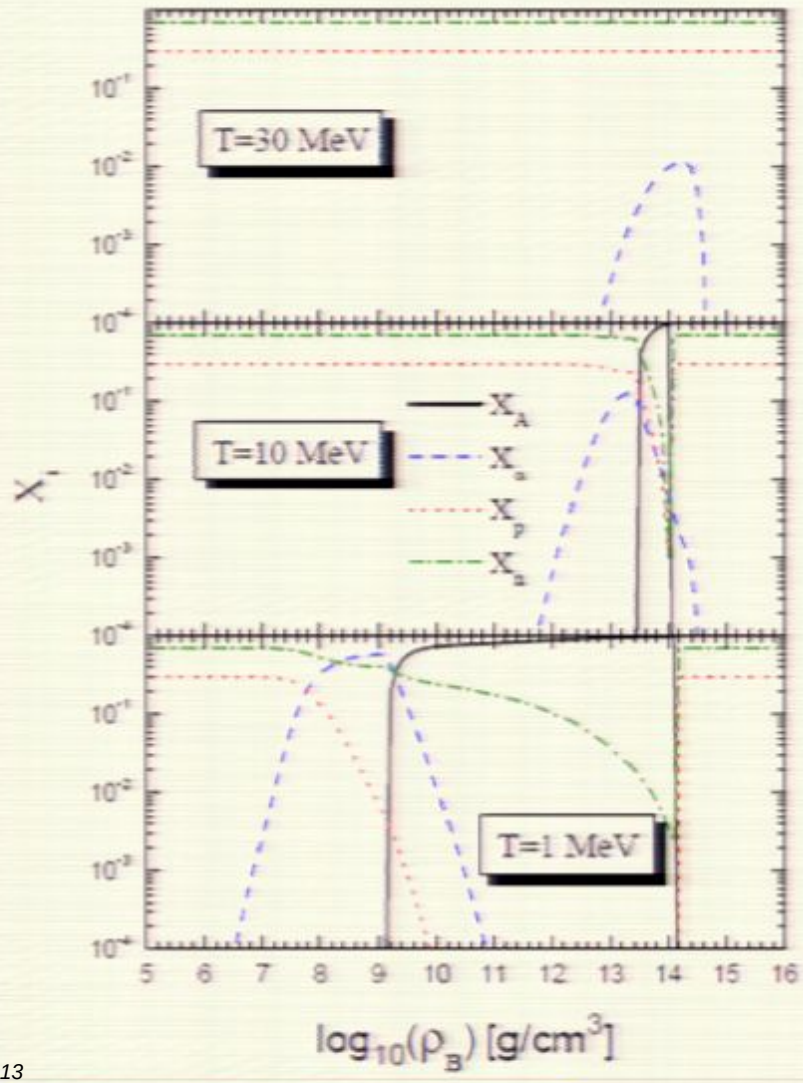
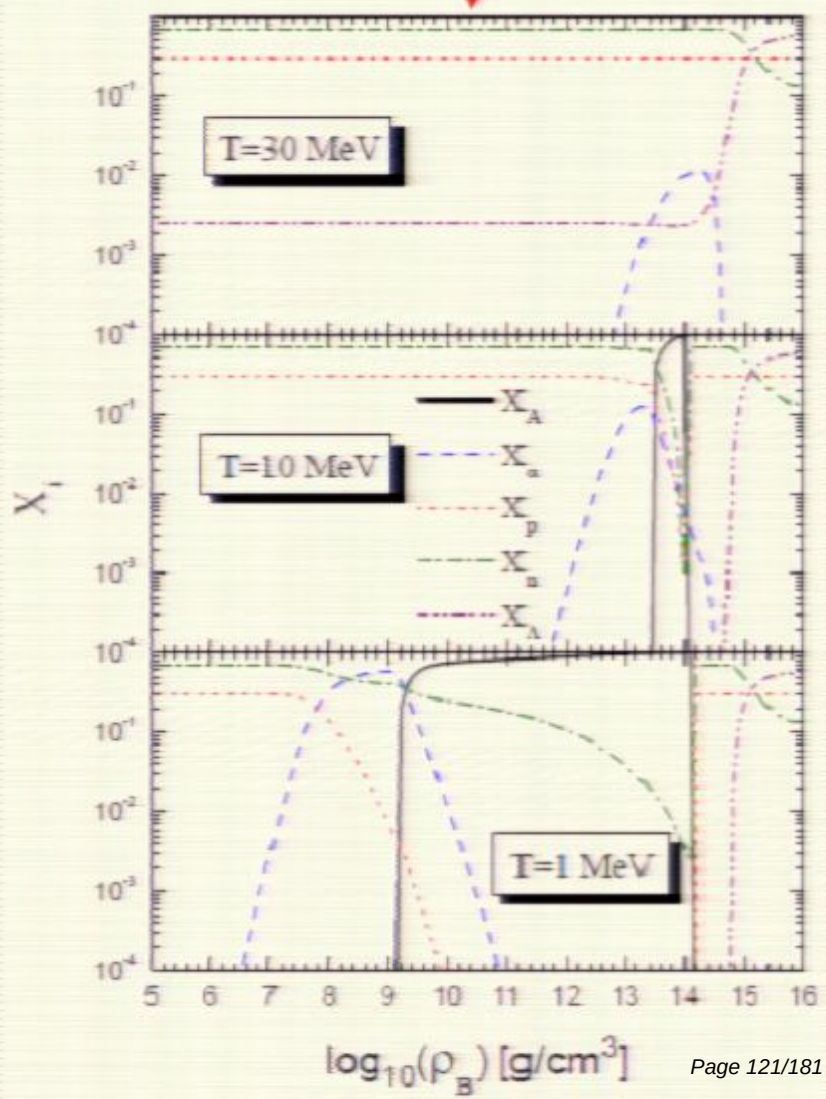


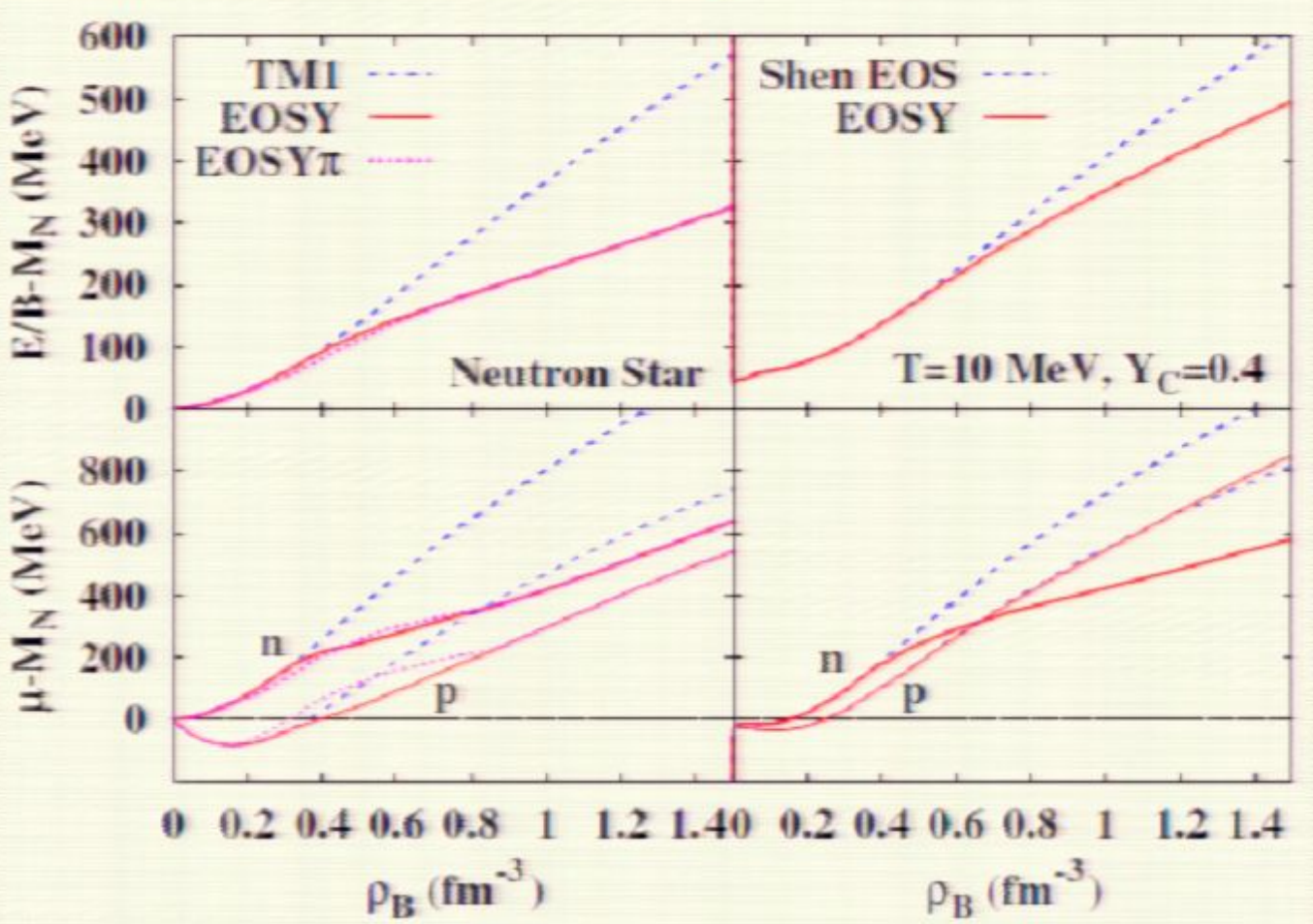


Effects of Λ hyperons

non-nucleonic degrees of freedom

- hyperons: Λ, Σ, Ξ
- boson condensates: π, K
- quarks: u, d, s

EOS for supernovae with hyperons



C. Ishizuka, A. Ohnishi, K. Tsubakihara, K. Sumiyoshi, S. Yamada, J. Phys. G 35 (2008) 085201

Pion condensate

PHYSICAL REVIEW C **80**, 038202 (2009)

Possibility of an s-wave pion condensate in neutron stars reexamined

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Pion condensate

PHYSICAL REVIEW C **80**, 038202 (2009)

Possibility of an s-wave pion condensate in neutron stars reexamined

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Experimental information

scattering experiments

NN scattering data > 4000

YN scattering data ~ 40

no YY scattering data

hypernuclear data

single-Λ hypernuclei > 30

double-Λ hypernuclei ~ 4

single-Σ hypernuclei ~ 1

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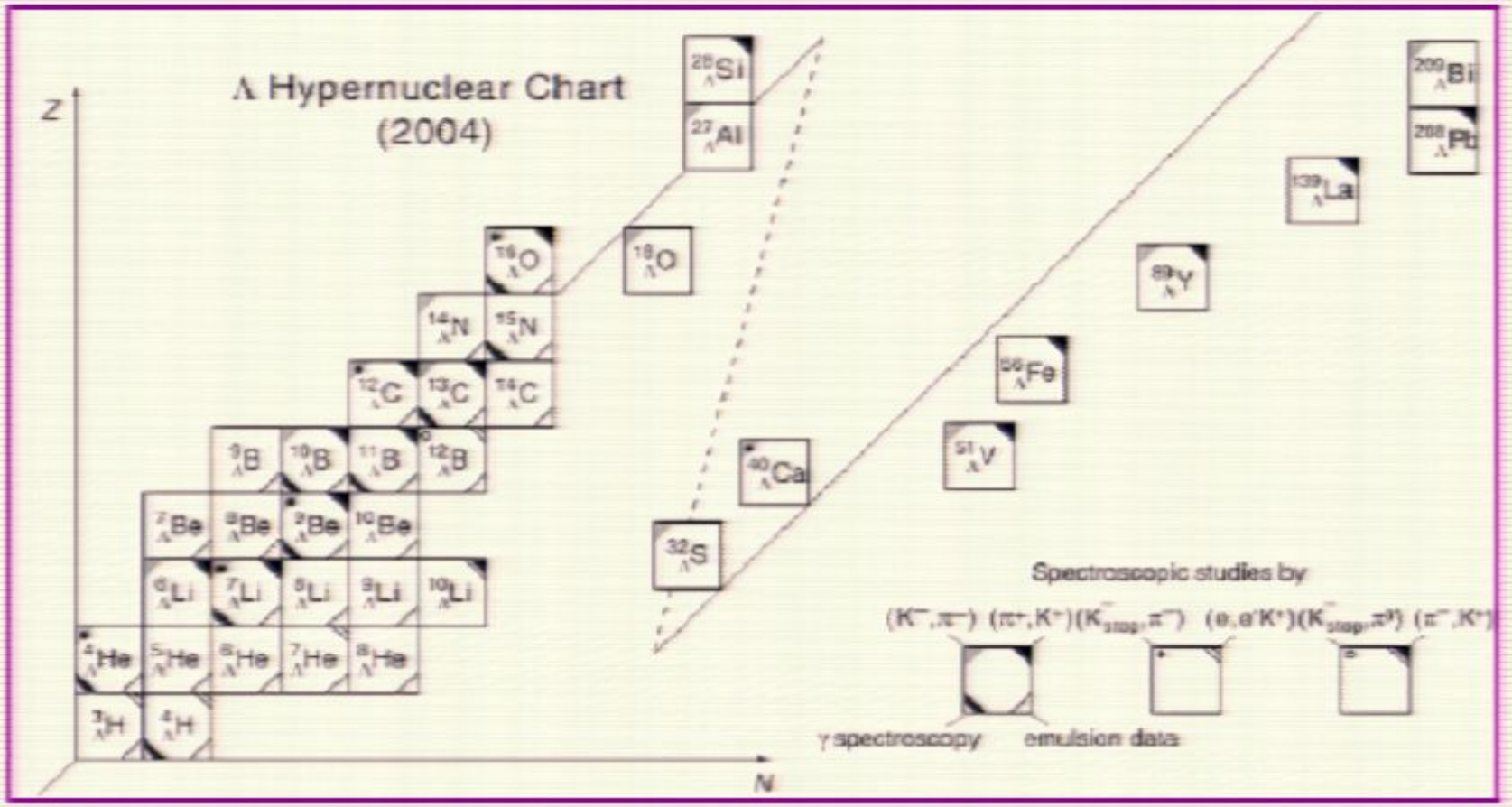
Hypernuclear Chart



O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564

Neutron star matter with hyperons

include baryon octet

$$n,\ p,\ \Lambda,\ \Sigma^-,$$
$$\Sigma^0,\ \Sigma^+,\ \Xi^-,\ \Xi^0$$

$U_\Lambda^{(N)} = -30$ MeV ✓

$U_\Sigma^{(N)} = +30$ MeV ?

$U_\Xi^{(N)} = -15$ MeV ?

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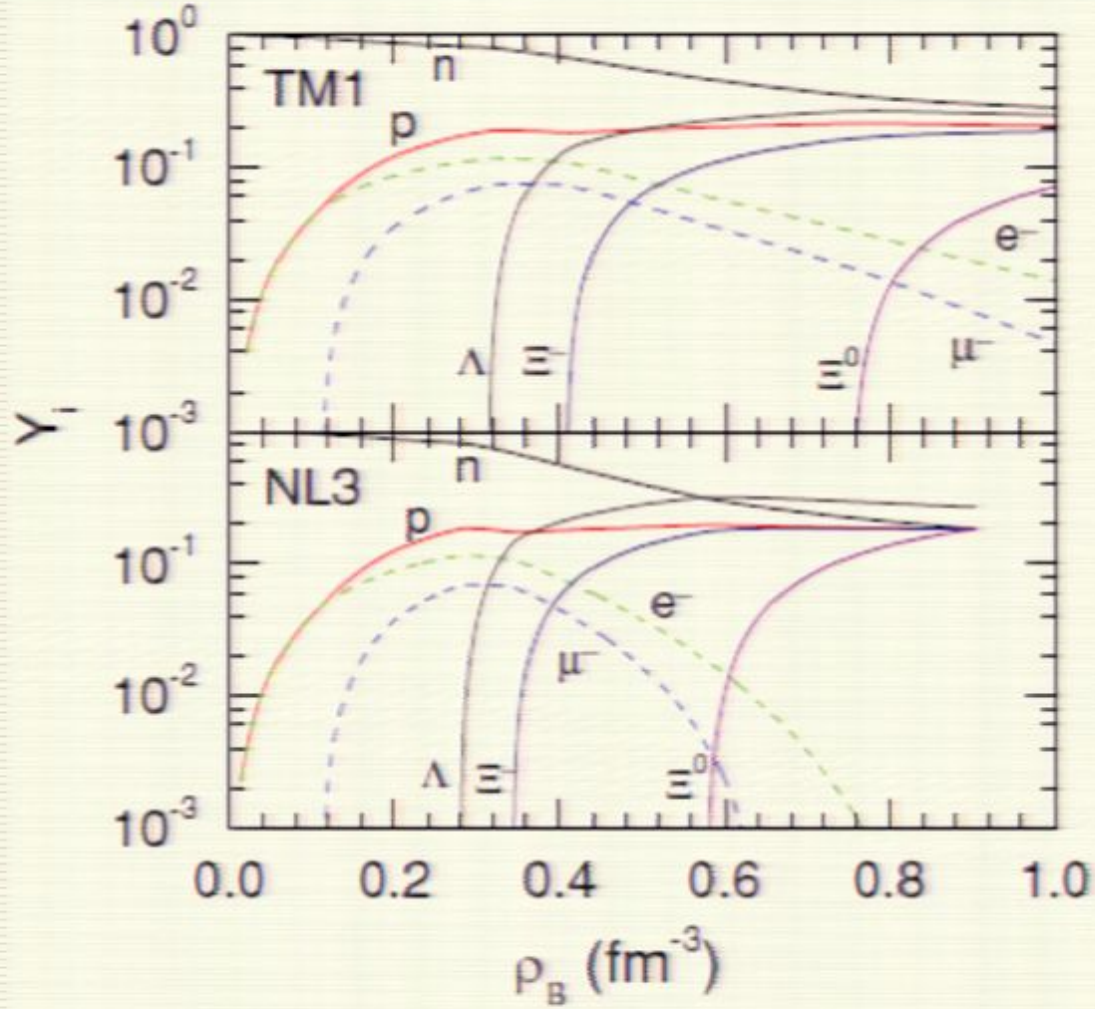

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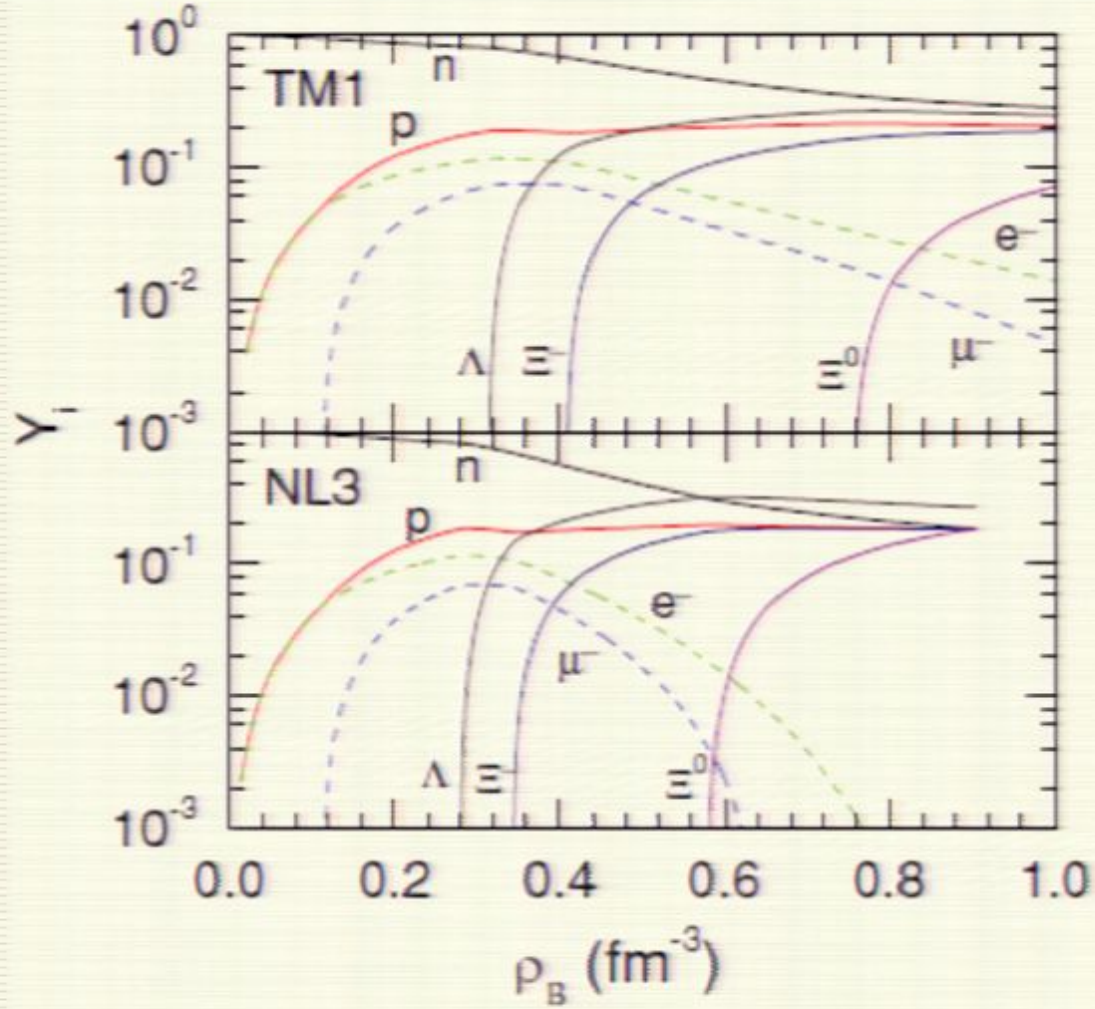

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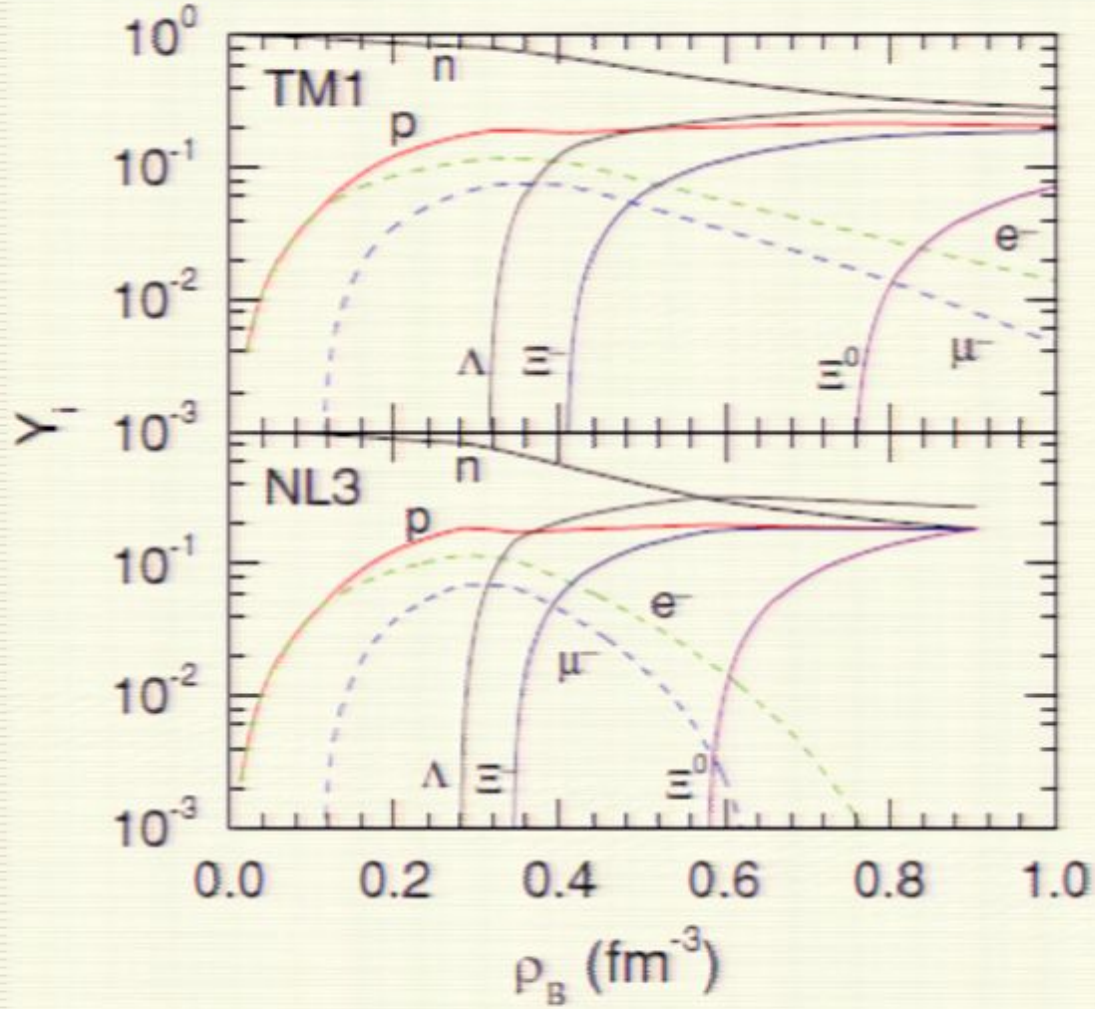

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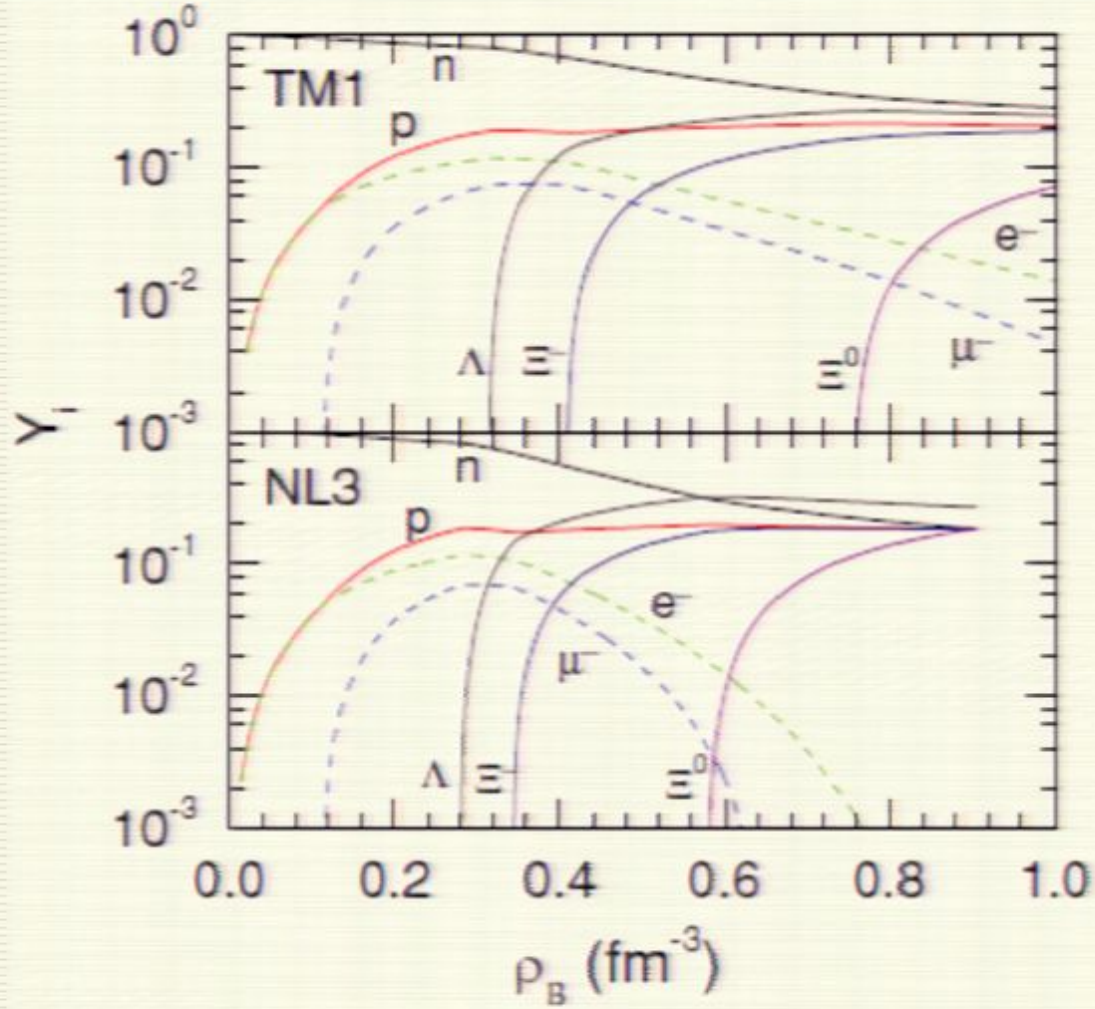

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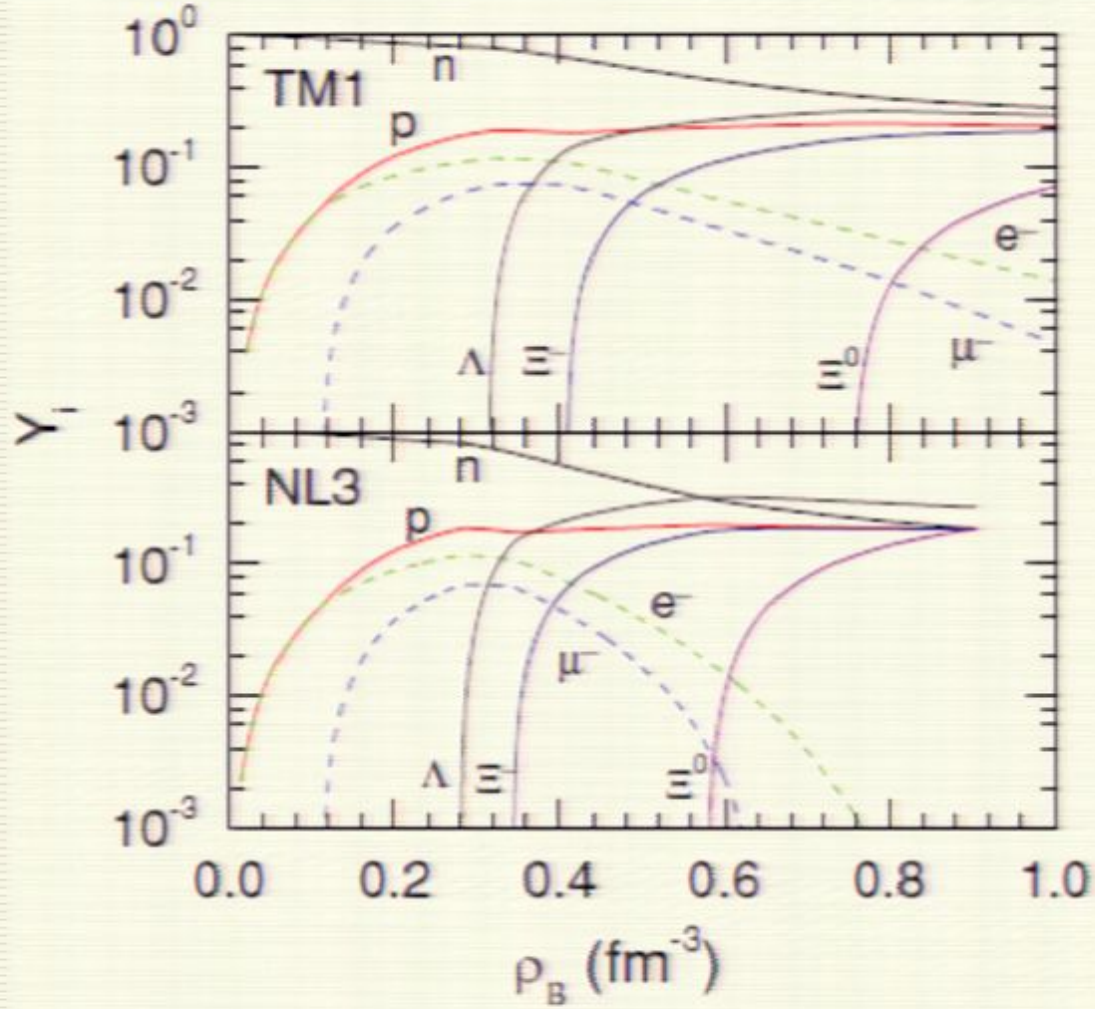

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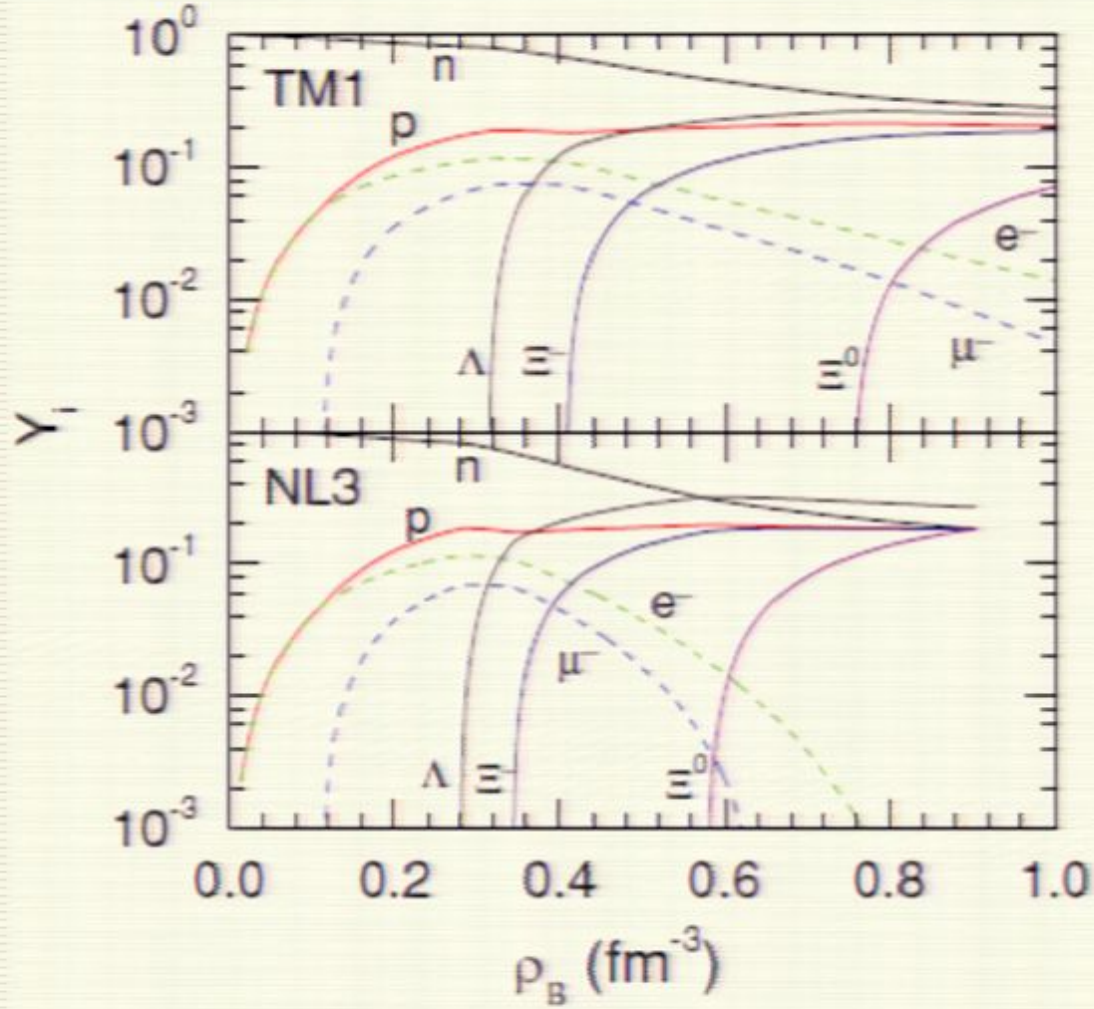

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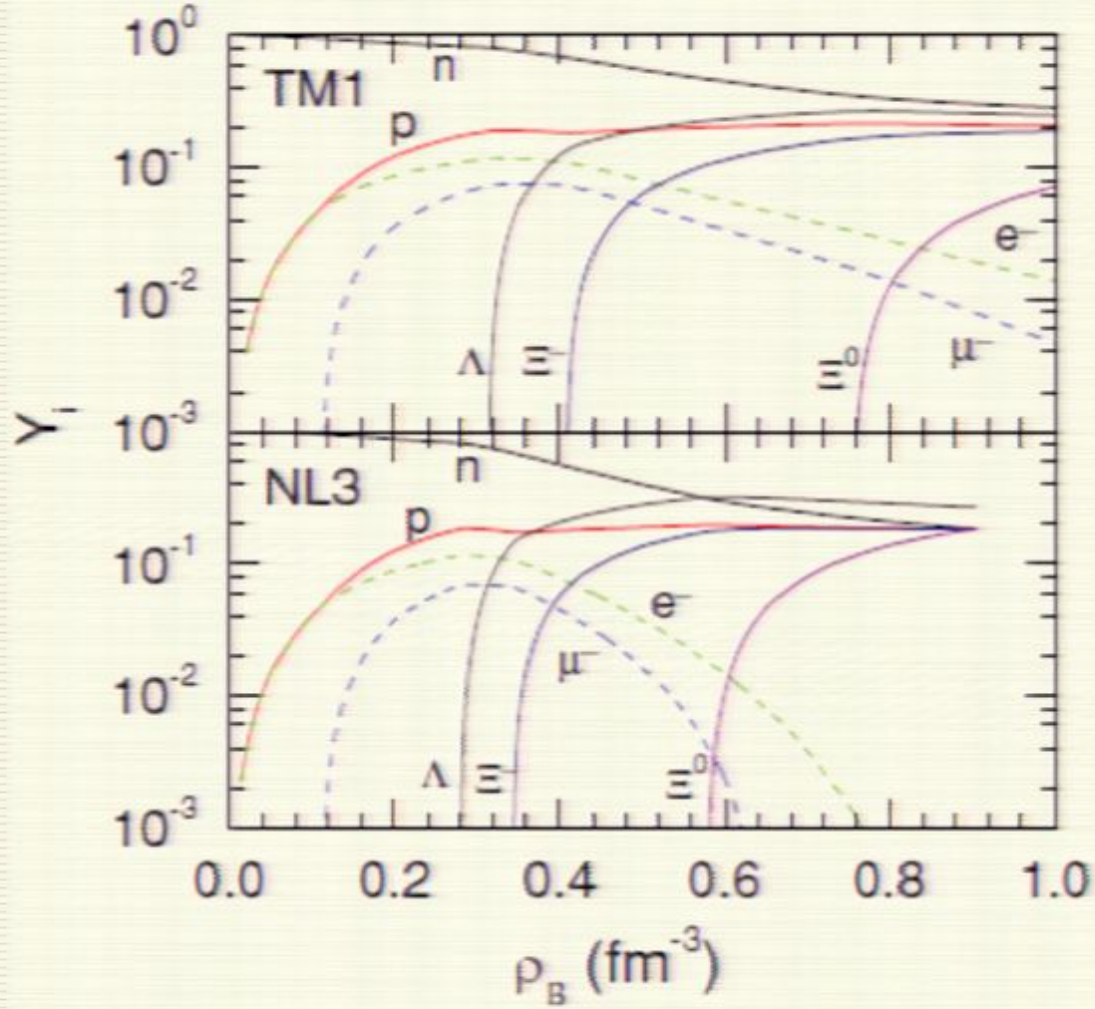

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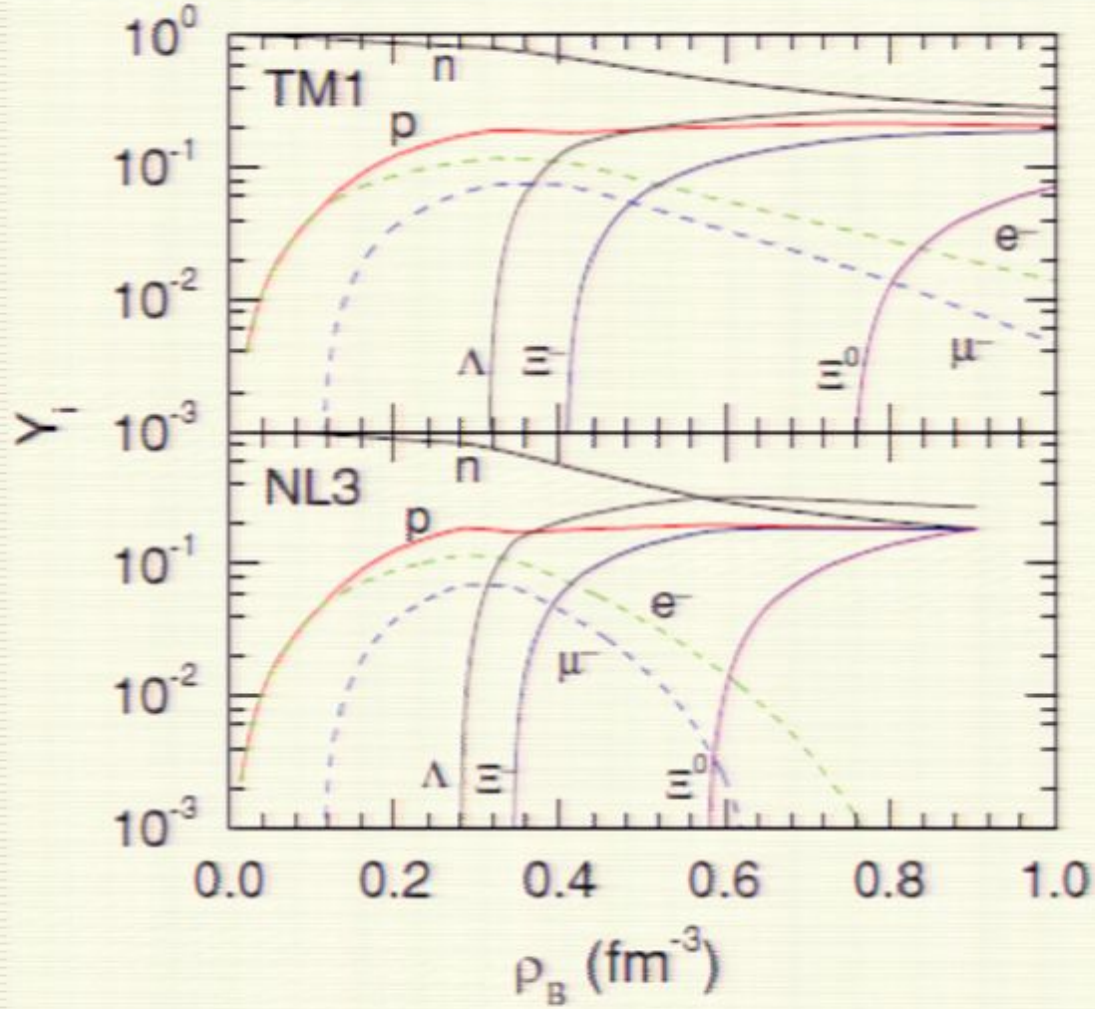

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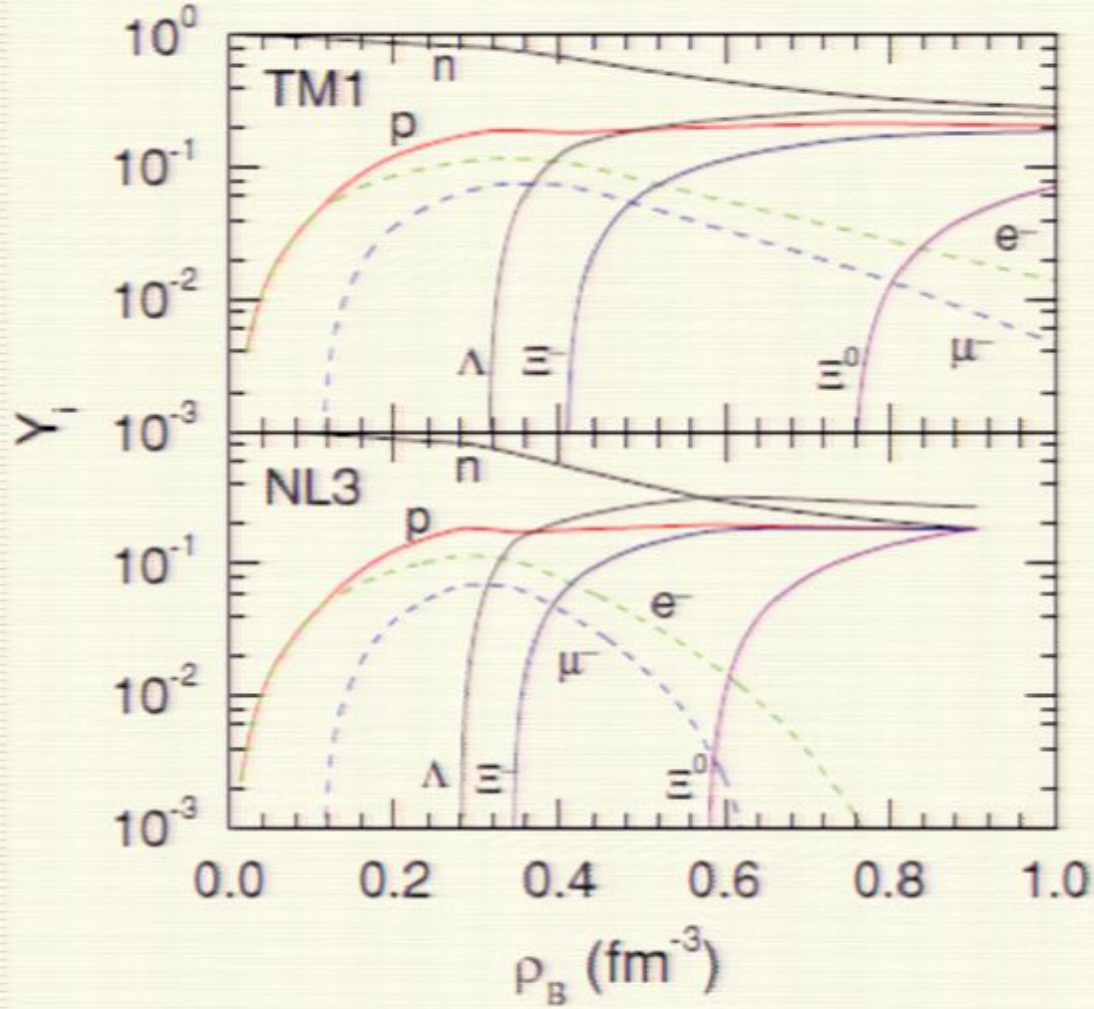

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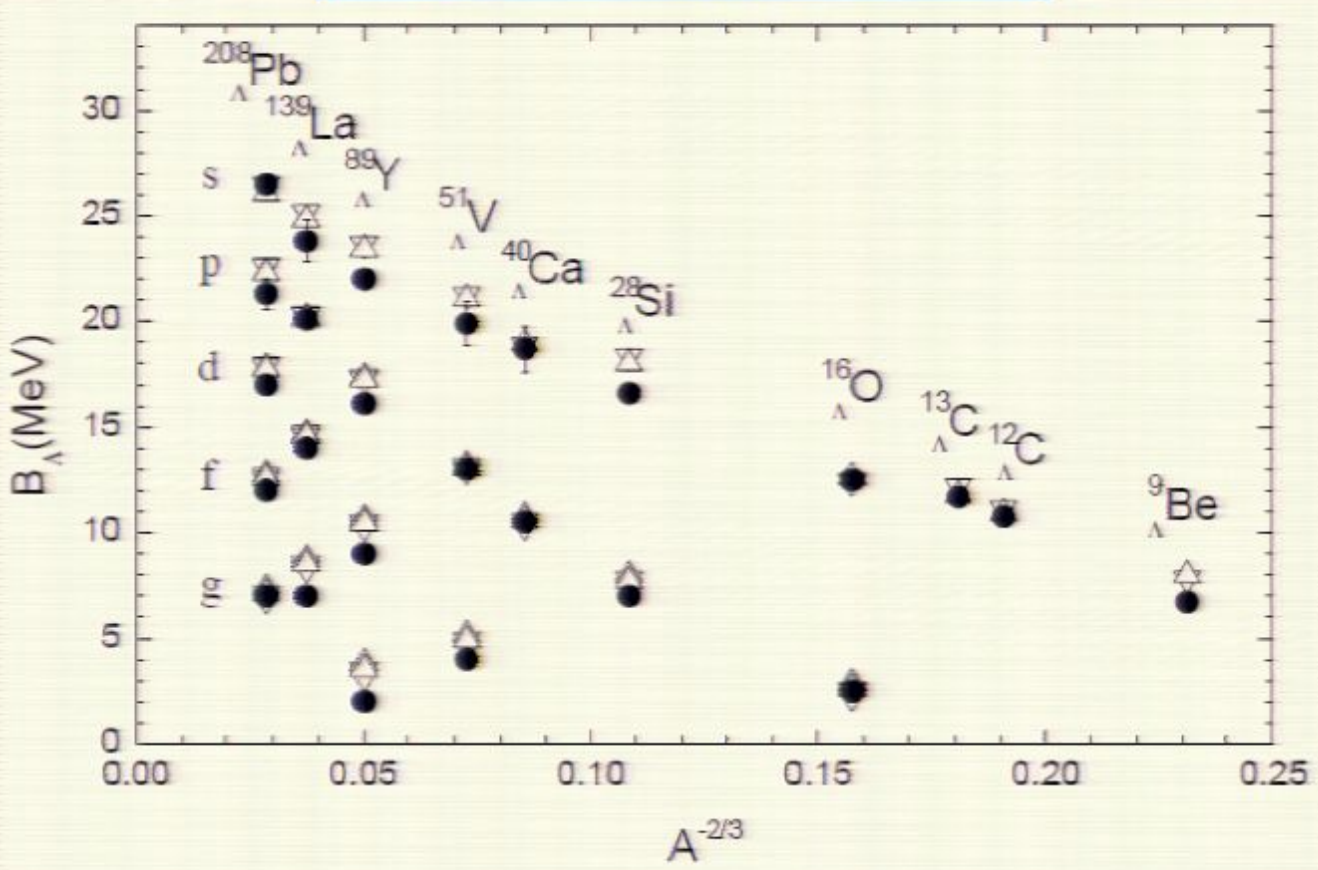
Hypernuclei in the RMF model

Single-Λ hypernuclei



H. Shen, F. Yang, H. Toki, Prog. Theor. Phys. 115 (2006) 325

Hypernuclei in the RMF model

Double-Λ hypernuclei

Table II. $B_{\Lambda\Lambda}$ and $\triangle B_{\Lambda\Lambda}$ of double-Λ hypernuclei. The calculated results of models 1 and 2 are denoted by 1 and 2, respectively. The available experimental data are taken from Refs. 10)–14).

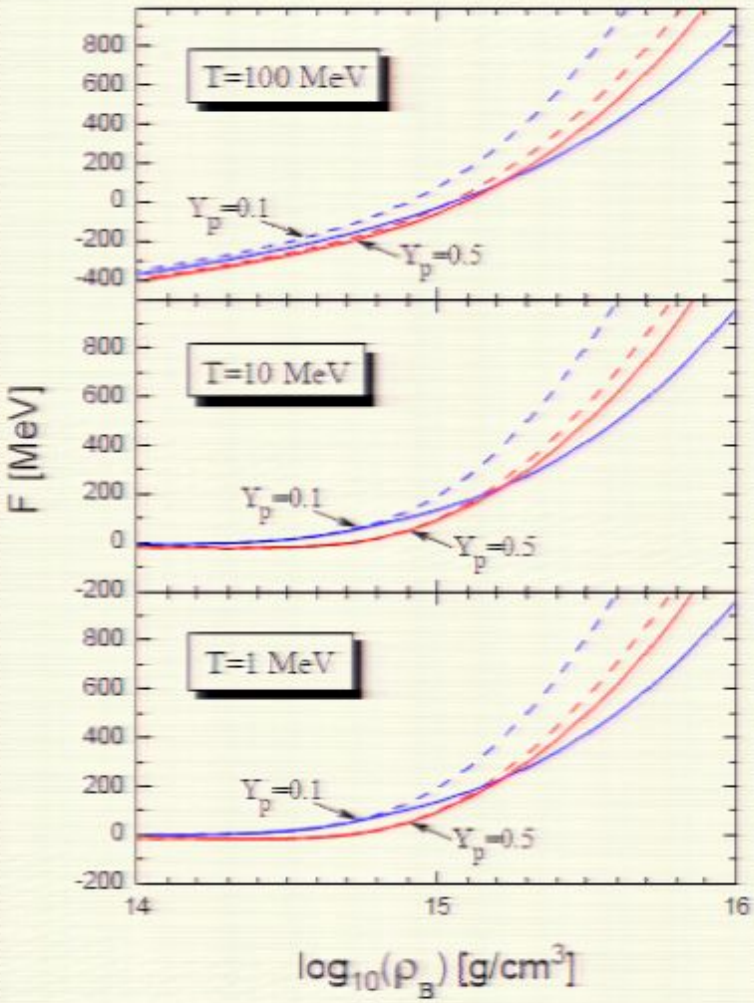
	$B_{\Lambda\Lambda}$	TM1		NL-SH		$\triangle B_{\Lambda\Lambda}$	TM1		NL-SH	
	exp.	1	2	1	2	exp.	1	2	1	2
${}^{6}_{\Lambda\Lambda}$He	7.25 ± 0.2	5.52	5.48	4.75	4.68	1.0 ± 0.2	1.07	1.03	1.08	1.01
${}^{10}_{\Lambda\Lambda}$Be	17.7 ± 0.4	16.34	16.28	16.03	15.94	4.3 ± 0.4	0.37	0.31	0.38	0.29
	14.6 ± 0.4					1.2 ± 0.4				
	8.5 ± 0.7					-4.9 ± 0.7				
${}^{13}_{\Lambda\Lambda}$B	27.5 ± 0.7	22.14	22.07	22.65	22.52	4.8 ± 0.7	0.26	0.19	0.33	0.21
${}^{18}_{\Lambda\Lambda}$O		25.89	25.85	25.30	25.23		0.14	0.10	0.14	0.07
${}^{42}_{\Lambda\Lambda}$Ca		38.15	38.13	37.90	37.86		0.04	0.02	0.04	0.00
${}^{92}_{\Lambda\Lambda}$Zr		47.11	47.10	47.73	47.71		0.03	0.02	0.04	0.02
${}^{210}_{\Lambda\Lambda}$Pb		52.19	52.19	53.03	53.02		0.03	0.02	0.02	0.02

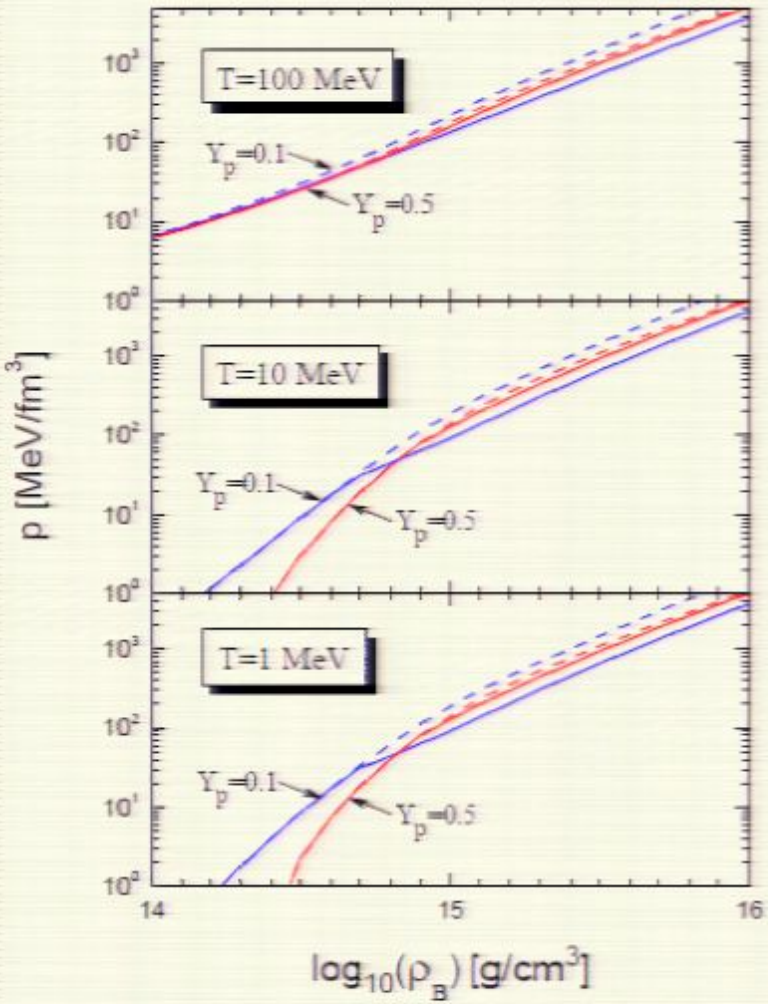
H. Shen, F. Yang, H. Toki, Prog. Theor. Phys. 115 (2006) 325

Effects of Λ hyperons

EOS2

EOS3





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