Matéria Nuclear Fria, Quente e Muito Quente

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26/08/2009

I – Motivação

II – A Física de Poucos Nucleons

III – Matéria Nuclear Fria

IV – Matéria Nuclear Quente

V – Matéria Nuclear Muito Quente

I – Motivação

- Entendimento das interações fortes.

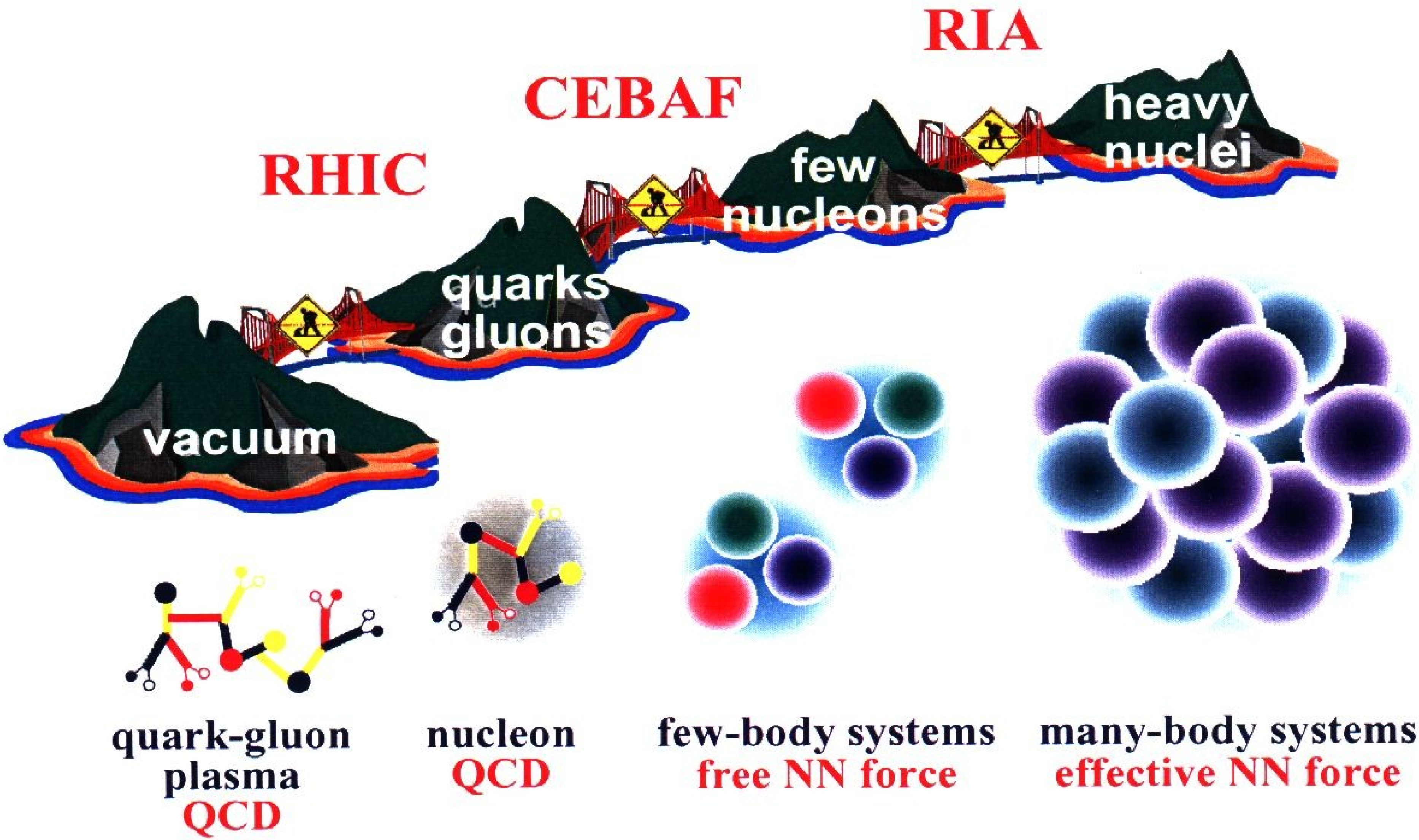
- Correlações entre sistemas de poucos e de muitos nucleons.

- Ordem da transição de fase em núcleos quentes.

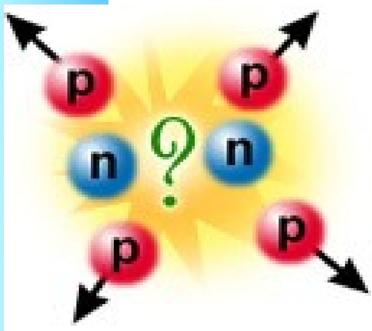
- A busca de um novo estado da matéria, o plasma de quarks e glúons, no laboratório (RHIC,LHC).

- Entendimento do diagrama de fase da QCD.

- Entendimento das várias simetrias e escalas da física.


RIA
CEBAF
RHIC
heavy nuclei
few nucleons
quarks gluons
vacuum
quark-gluon plasma
QCD
nucleon
QCD
few-body systems
free NN force
many-body systems
effective NN force

II – A Física de Poucos Nucleons



O que mantém o núcleo unido?

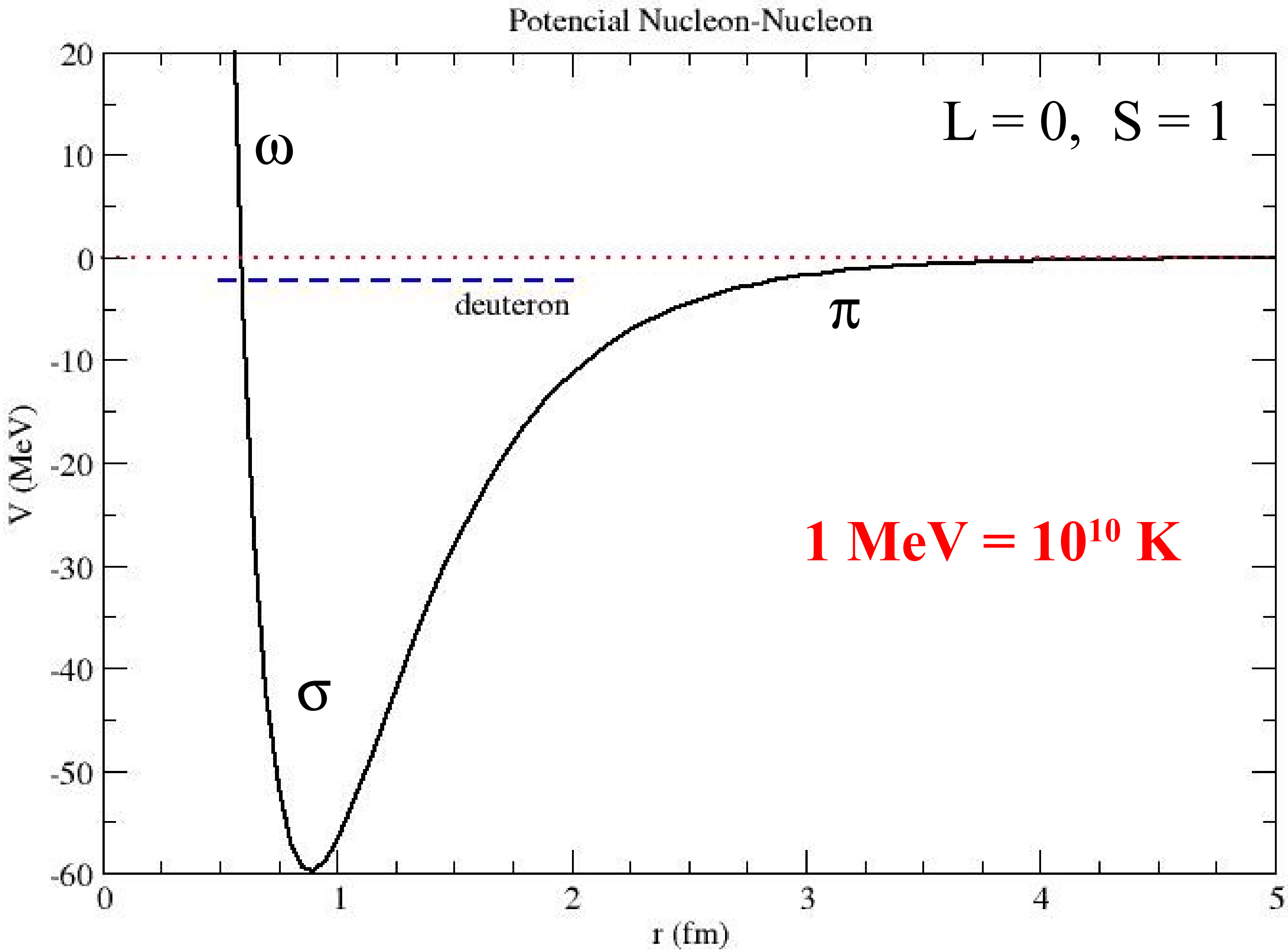
Interação Nuclear Forte

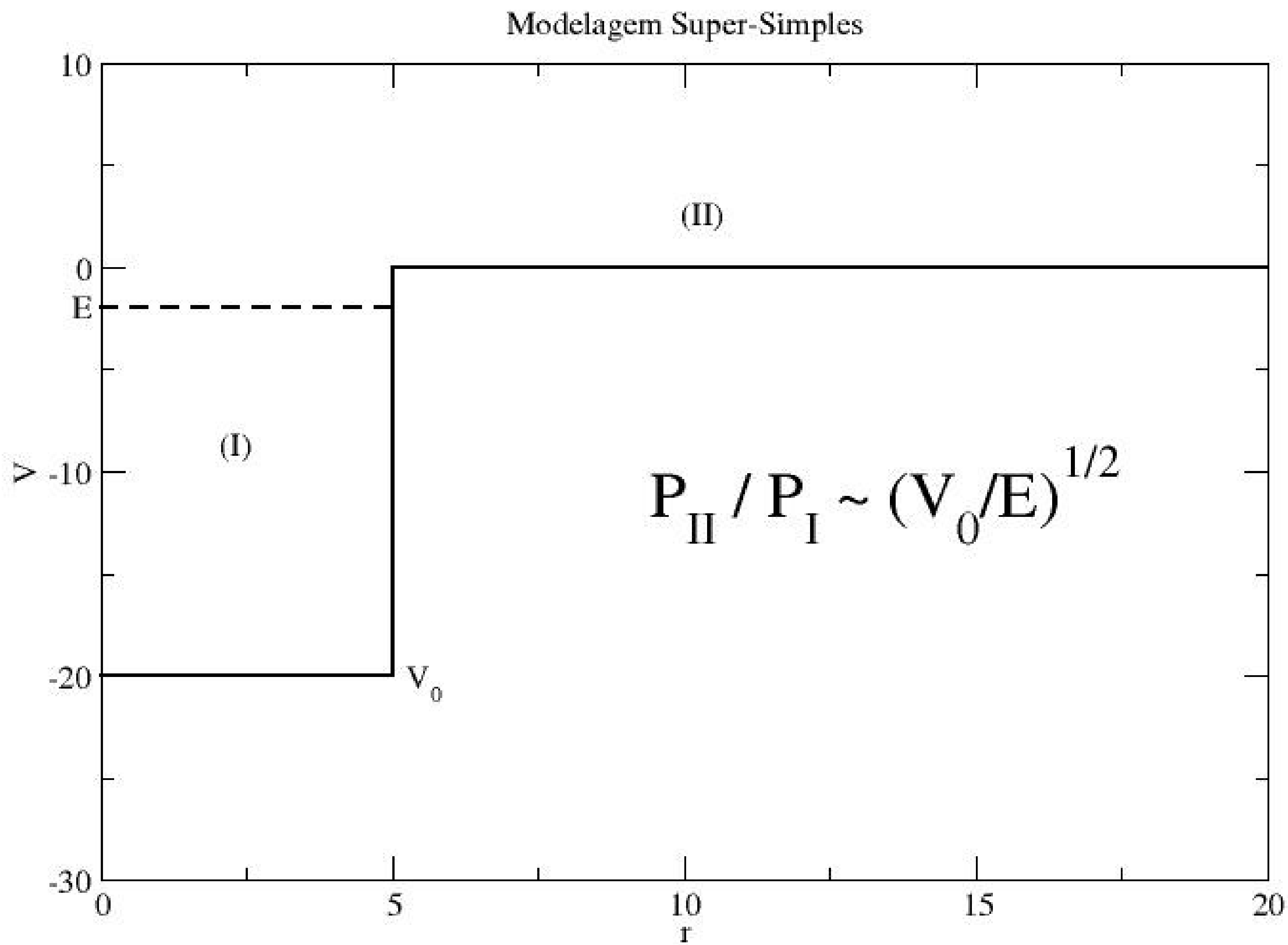
Yukawa (1935) → píon

(M_{π} ~ 300 M_e) deduzido do alcance da força nuclear

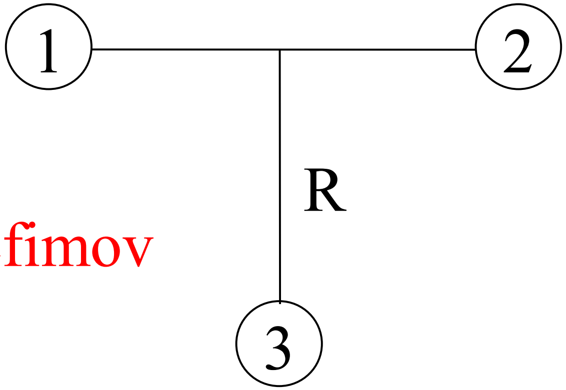
↓

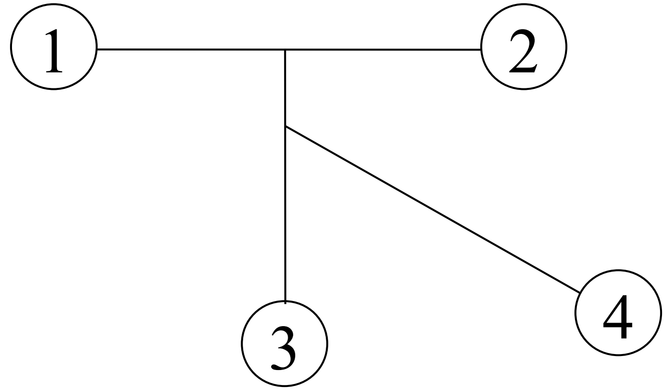
1947 (César Lattes)


Potencial Nucleon-Nucleon
L = 0, S = 1
ω
σ
π
deuteron
1 MeV = 10^10 K
V (MeV)
r (fm)
20
10
0
-10
-20
-30
-40
-50
-60
0
1
2
3
4
5


Modelagem Super-Simples
10
0
E
-10
-20
-30
V
0
5
10
15
20
r
(I)
(II)
V_0
$P_{II} / P_I \sim (V_0/E)^{1/2}$

Efeito Efimov





$$V(R) = -\frac{1}{\nu}\left[\frac{2}{a}\frac{e^{-R/a}}{R} + \frac{e^{-2R/a}}{R^2}\right],$$

3D

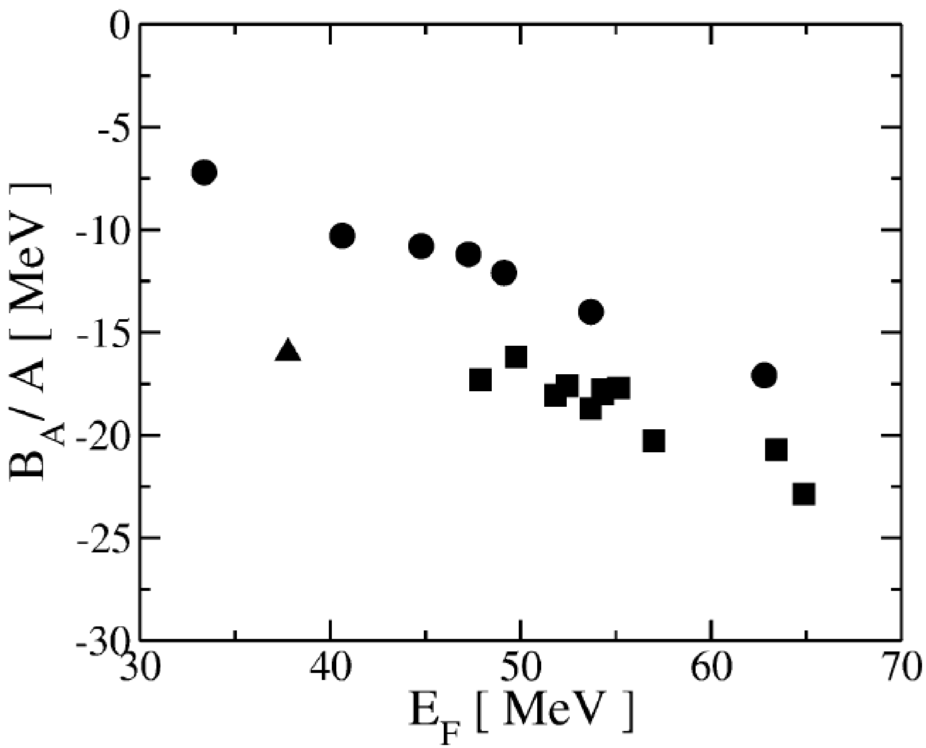
$$\left[\frac{1}{2m}\frac{d^2}{dR^2} + \frac{\ell(\ell+1)}{2mR^2} + V(R)\right]\phi = (B_2 - B_3)\phi.$$

Scaling: $R' = \sqrt{B_2}R, \; V(R) = B_2 V(R'), \; B_2 \sim 1/a^2$

$$\left[\frac{1}{2}\frac{d^2}{dR'^2} + \frac{\ell(\ell+1)}{2R'^2} + V(R')\right]\phi = \left(1 - \frac{B_3}{B_2}\right)\phi$$

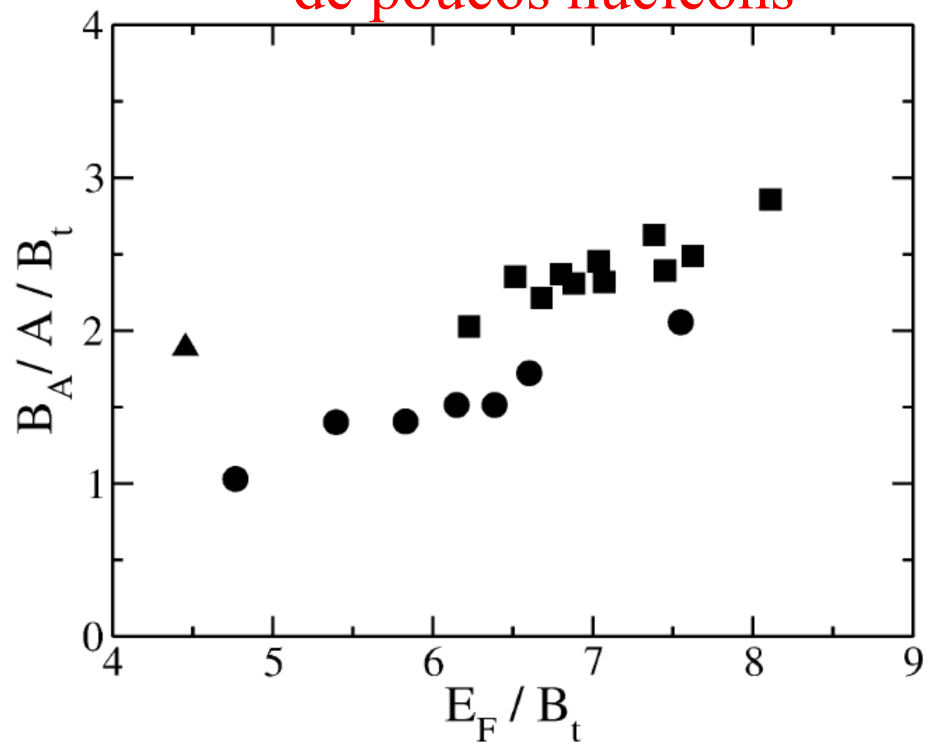
A. D. , T. Frederico, PRC 53, 62 (1996).

III – Matéria Nuclear Fria



Linha de Coester

Conexão com escalas de poucos nucleons



A. D. , *et al*, PLB 634, 185 (2006).

Muitos Nucleons (NR) - Skyrme

$$P = \frac{t_0}{8}\rho^2[2(x_0+2)-(2x_0+1)H_2] + \frac{t_3}{48}(\sigma+1)\rho^{\sigma+2}$$
$$\times [2(x_3+2)-(2x_3+1)H_2]$$
$$+\frac{1}{8}\left(\frac{3\pi^2}{2}\right)^{2/3}\rho^{8/3}(aH_{5/3}+bH_{8/3})$$
$$+\frac{2}{3}\int d^3p\,\frac{p^2}{2M}\frac{1}{e^{\beta(p^2-p_{F_q}^2)/2M}+1},$$

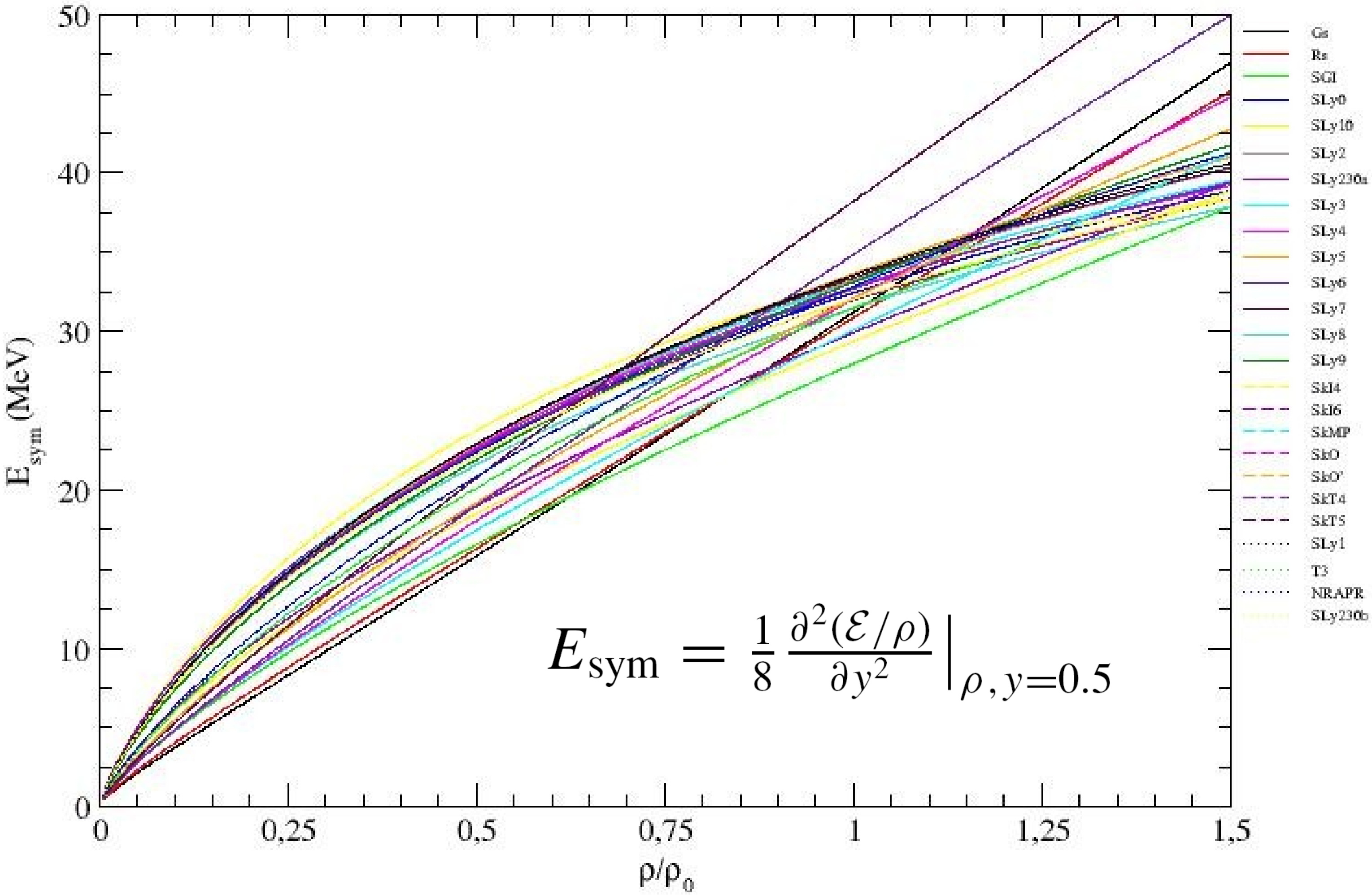
$$y = Z/A$$

$$H_n(y) = 2^{n-1}[y^n + (1-y)^n]$$

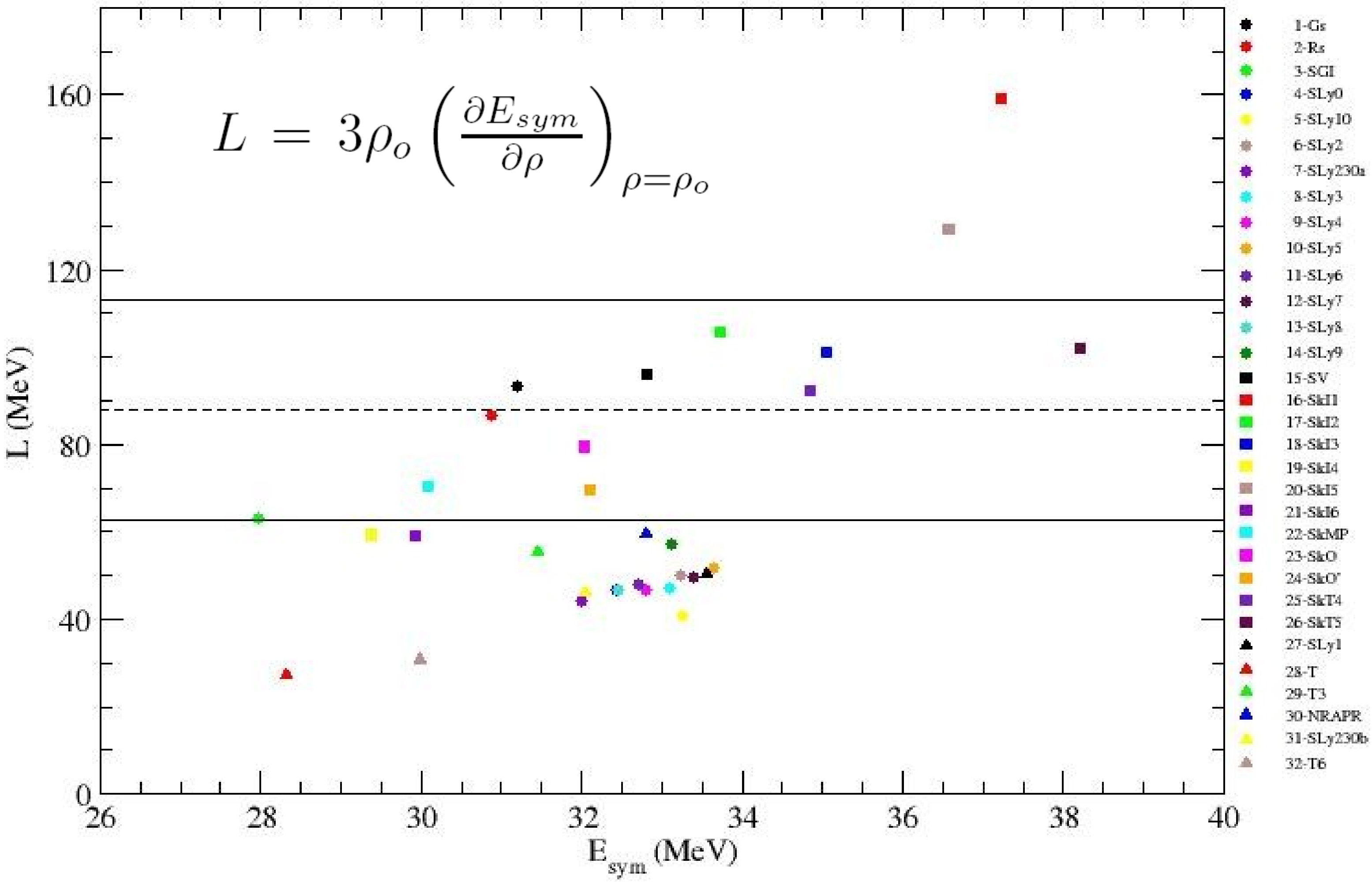
Há mais de 100 parametrizações diferentes !

↓

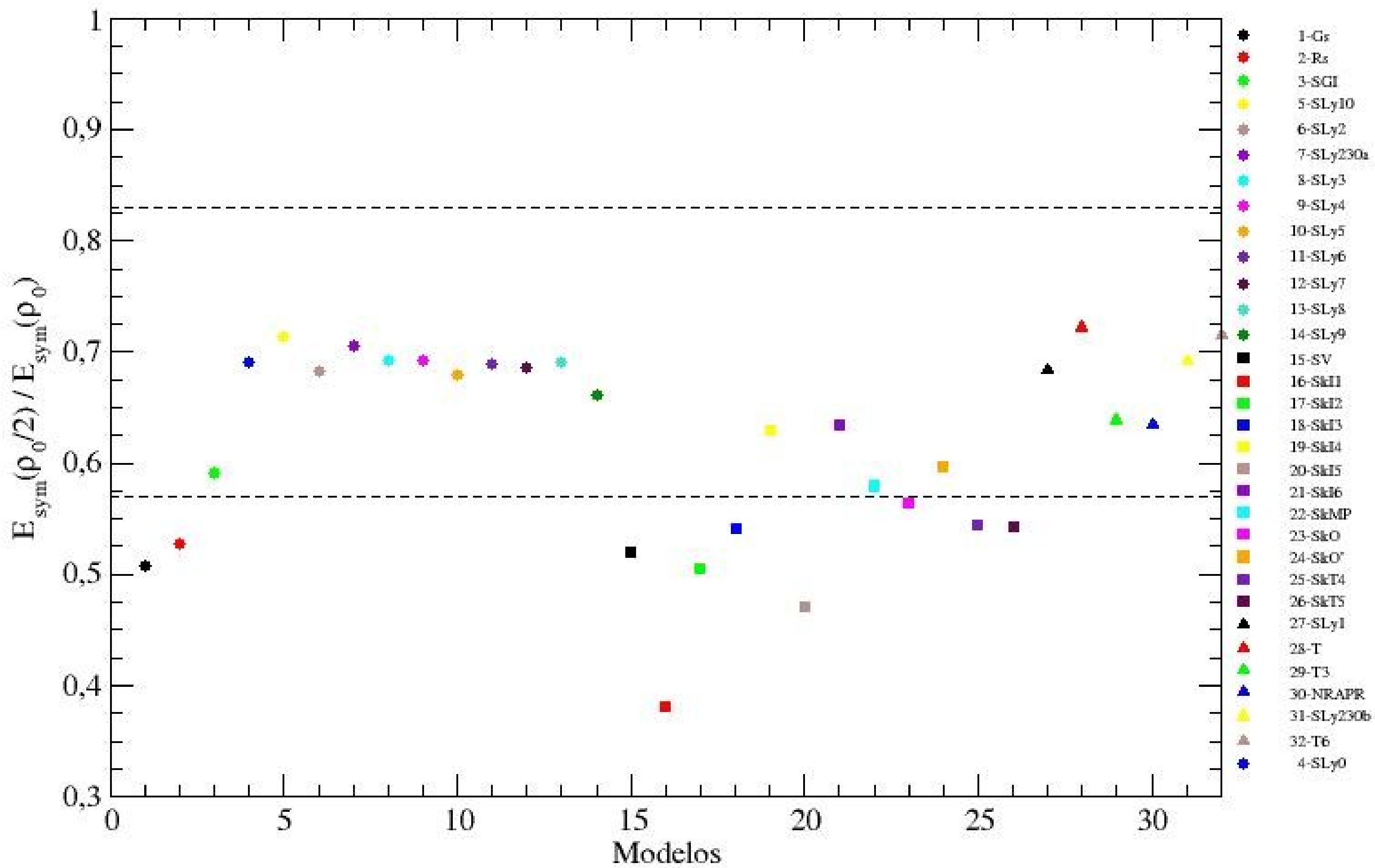
É importante selecioná-los, já em T = 0


50
40
30
20
10
0
E_{sym} (MeV)
0
0,25
0,5
0,75
1
1,25
1,5
ρ/ρ_0
Gs
Rs
SGI
SLy0
SLy10
SLy2
SLy230a
SLy3
SLy4
SLy5
SLy6
SLy7
SLy8
SLy9
SkI4
SkI6
SkMP
SkO
SkO'
SkT4
SkT5
SLy1
T3
NRAPR
SLy230b
$$E_{\mathrm{sym}} = \frac{1}{8}\frac{\partial^2(\mathcal{E}/\rho)}{\partial y^2}\bigg|_{\rho, y=0.5}$$

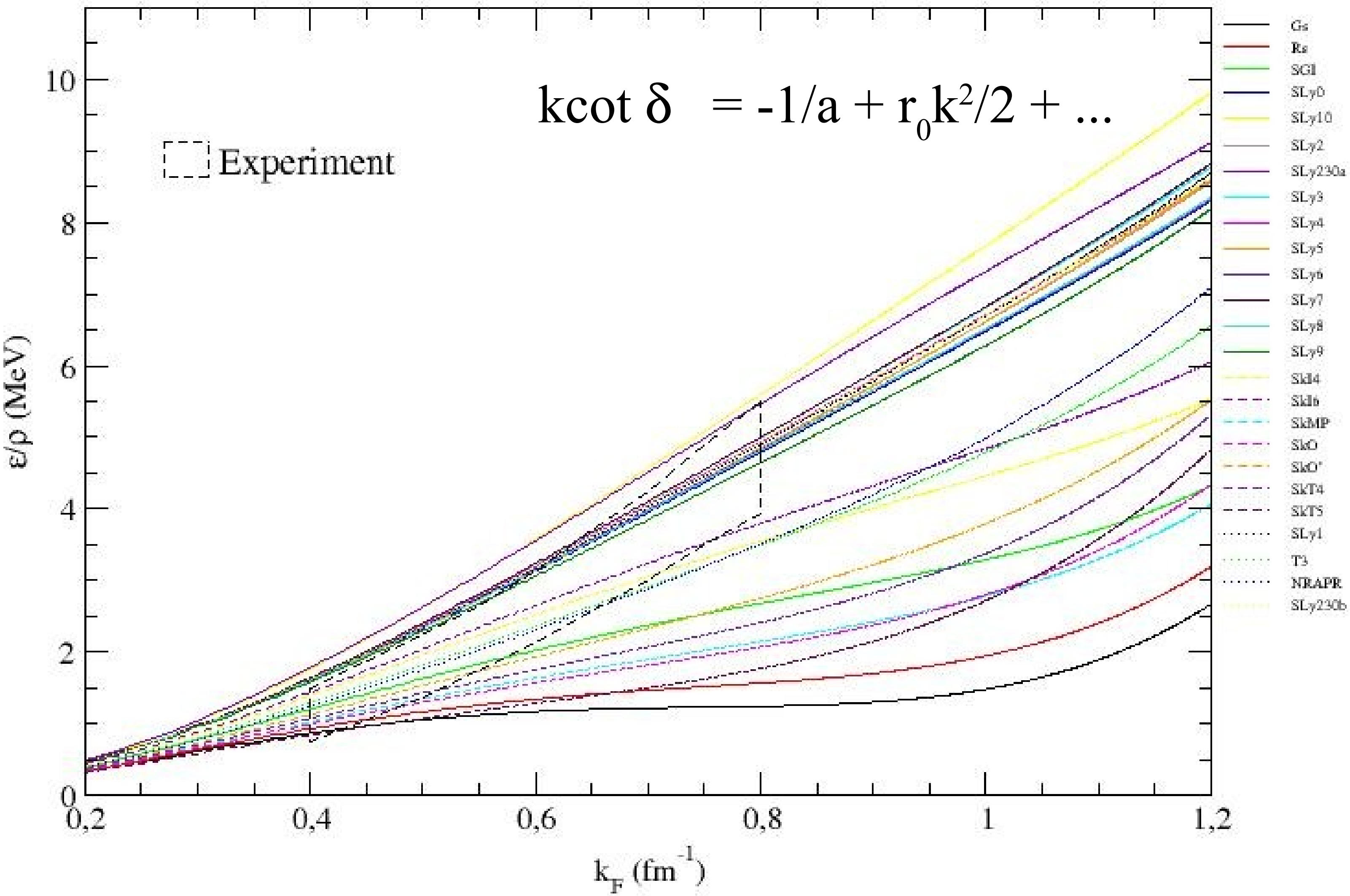
Limites: 88 +/- 25 (113 - 63) MeV



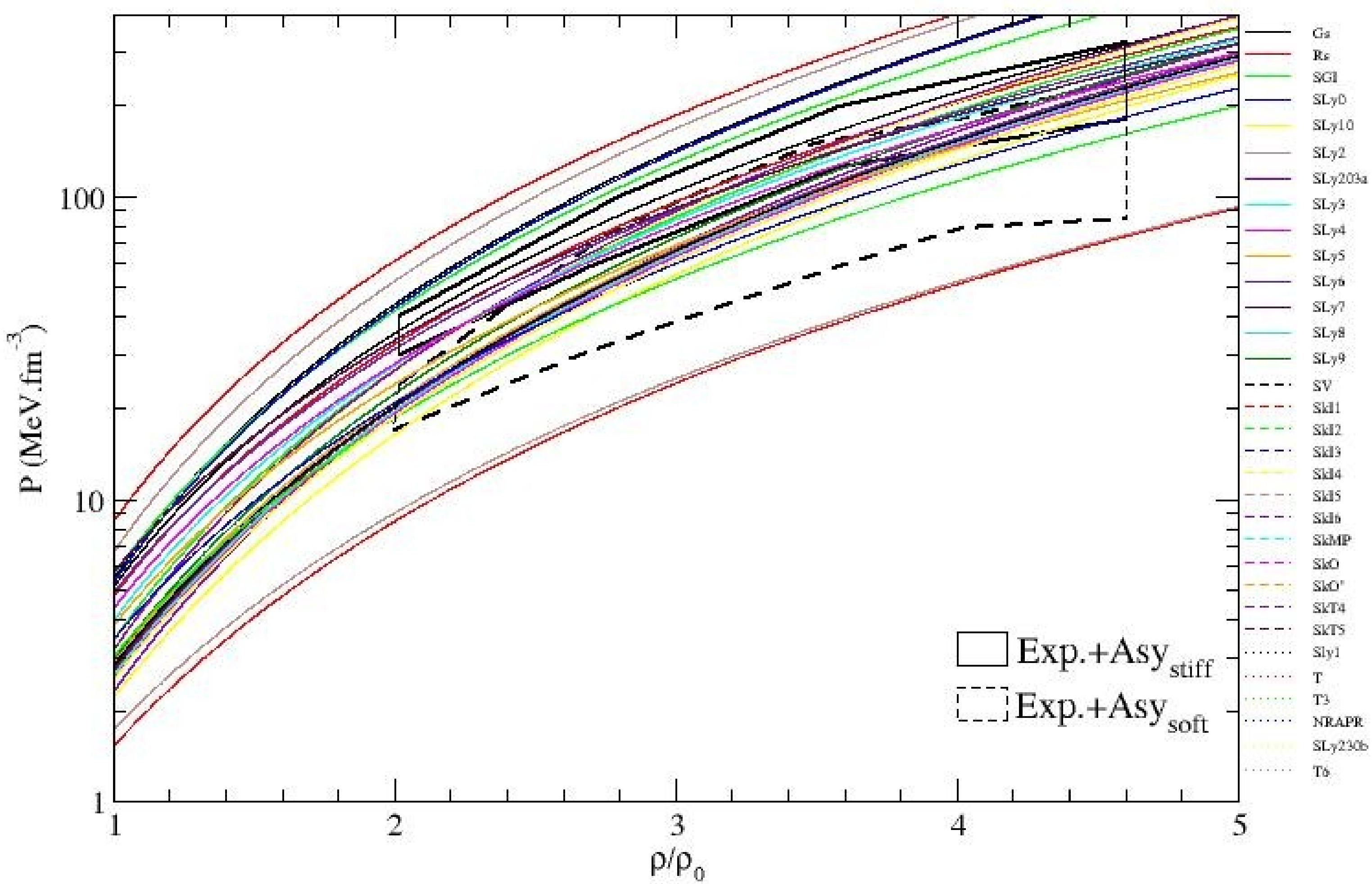
Limites: 0.57 - 0.83



PNM (Pure Neutron Matter)



PNM (Pure Neutron Matter)



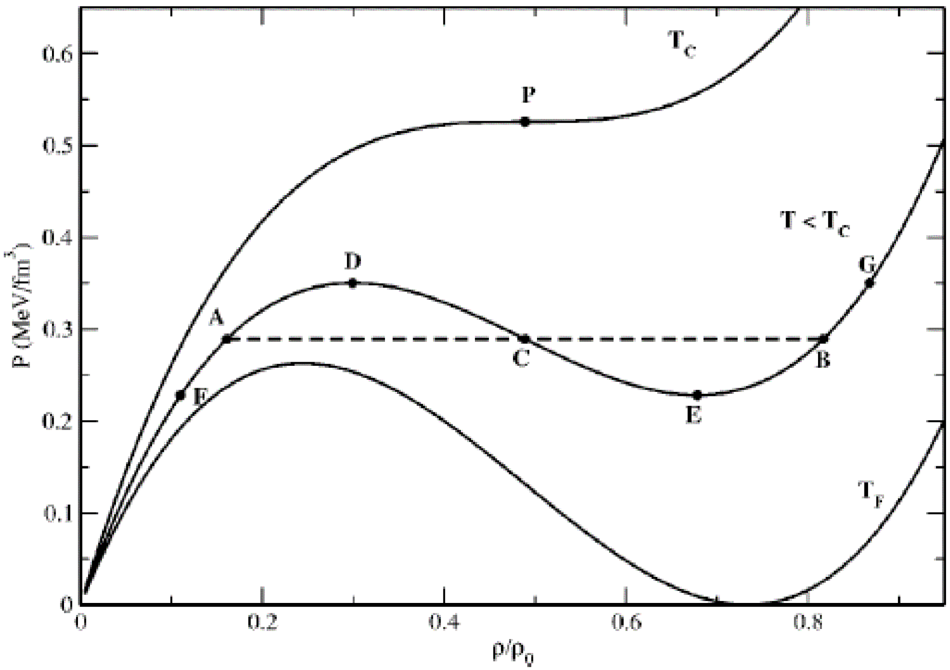
IV – Matéria Nuclear Quente

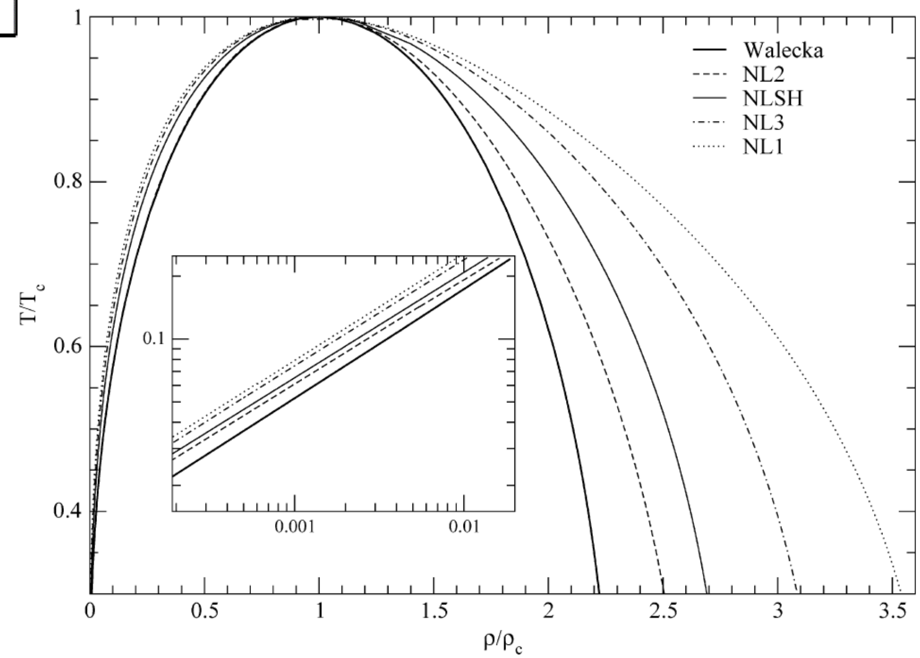
$$\mathcal{E}[M^*,\rho] = \frac{m_s^2}{g_s^2}\Phi^2\left(\frac{1}{2}+\frac{c}{3}\frac{\Phi}{m_s^2 g_s}+\frac{d}{4}\frac{\Phi^2}{m_s^2 g_s^2}\right) + \frac{\gamma}{(2\pi)^3}\int d^3k\sqrt{\mathbf{k}^2+M^{*2}}(n_k+\bar{n}_k) - \frac{m_v^2}{2g_v^2}W^2 + W\rho,$$

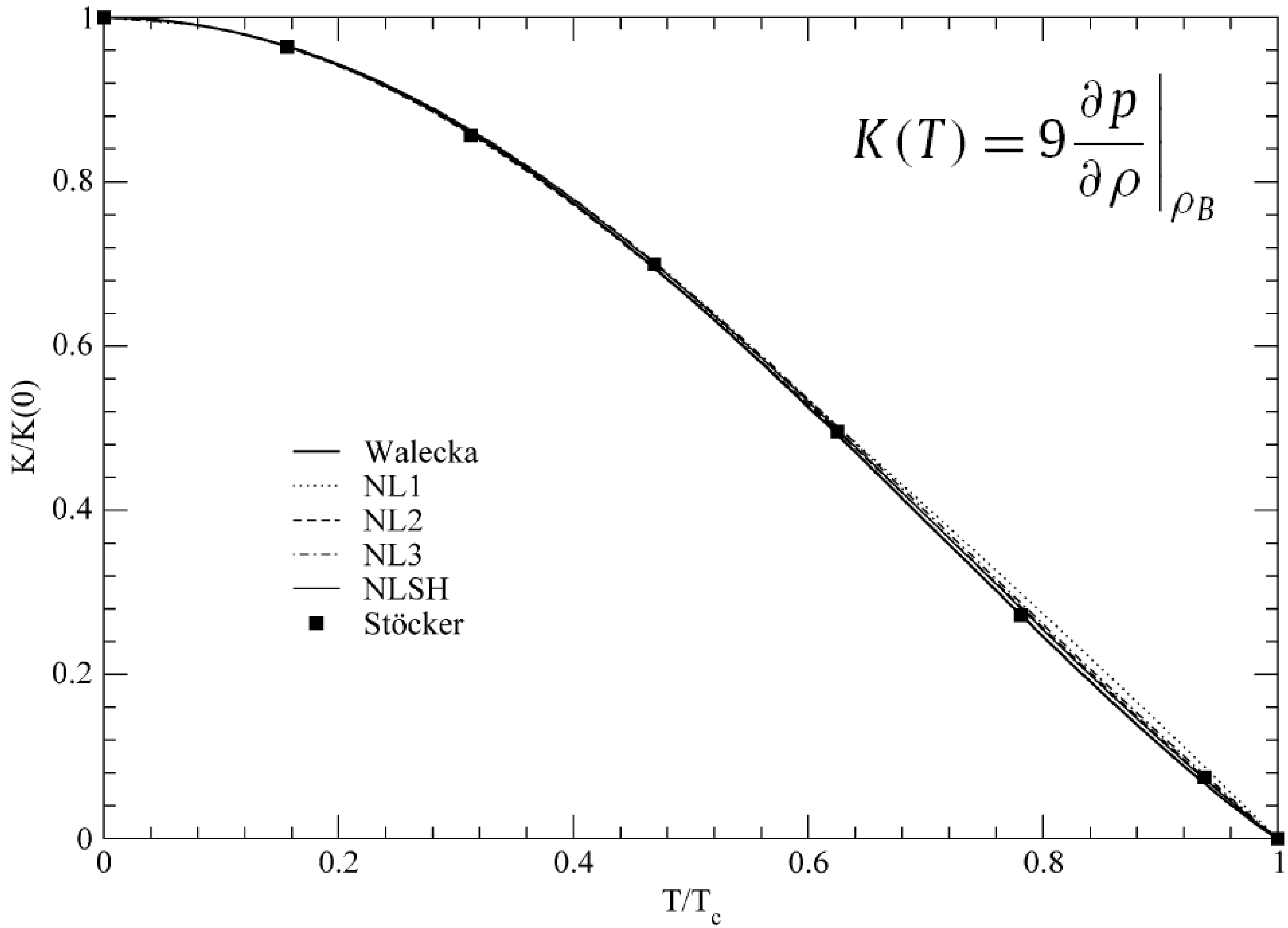
$$p[M^*,\rho] = -\frac{m_s^2}{g_s^2}\Phi^2\left(\frac{1}{2}+\frac{c}{3}\frac{\Phi}{m_s^2 g_s}+\frac{d}{4}\frac{\Phi^2}{m_s^2 g_s^2}\right) + \frac{1}{3}\frac{\gamma}{(2\pi)^3}\int d^3k\frac{k^2}{E^*(k)}(n_k+\bar{n}_k) - \frac{m_v^2}{2g_v^2}W^2 + W\rho.$$

$$M^* = M - c\frac{\Phi^2}{m_s^2 g_s} - d\frac{\Phi^3}{m_s^2 g_s^2} - \frac{g_s^2}{m_s^2}\frac{\gamma}{(2\pi)^3}\int d^3k\frac{M^*}{E^*(k)}(n_k+\bar{n}_k)$$

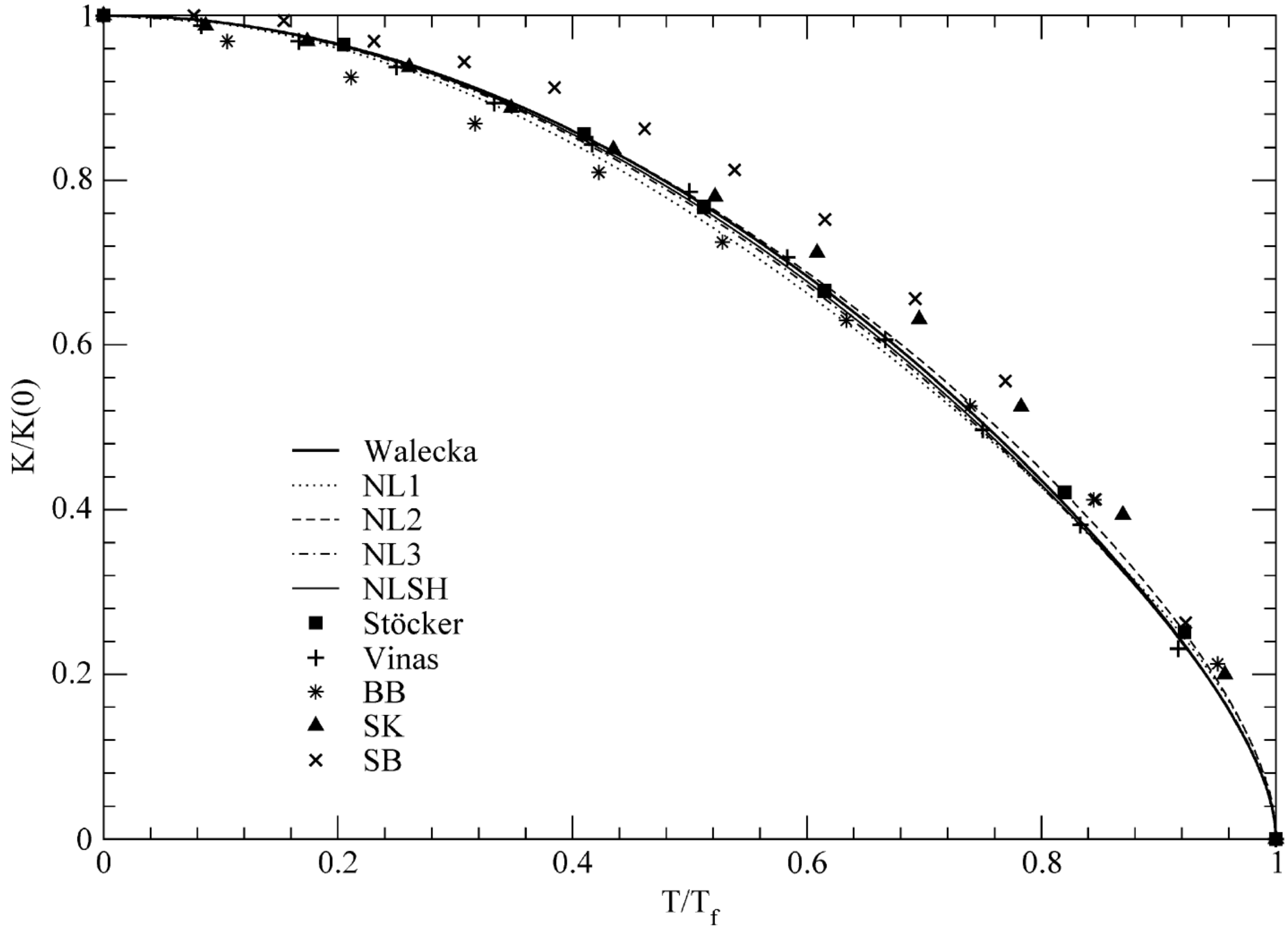
$$\rho = \frac{\gamma}{(2\pi)^3}\int d^3k\,(n_k-\bar{n}_k).$$


T_c
P
T < T_c
D
G
A
C
B
F
E
T_F
P (MeV/fm^3)
ρ/ρ_0

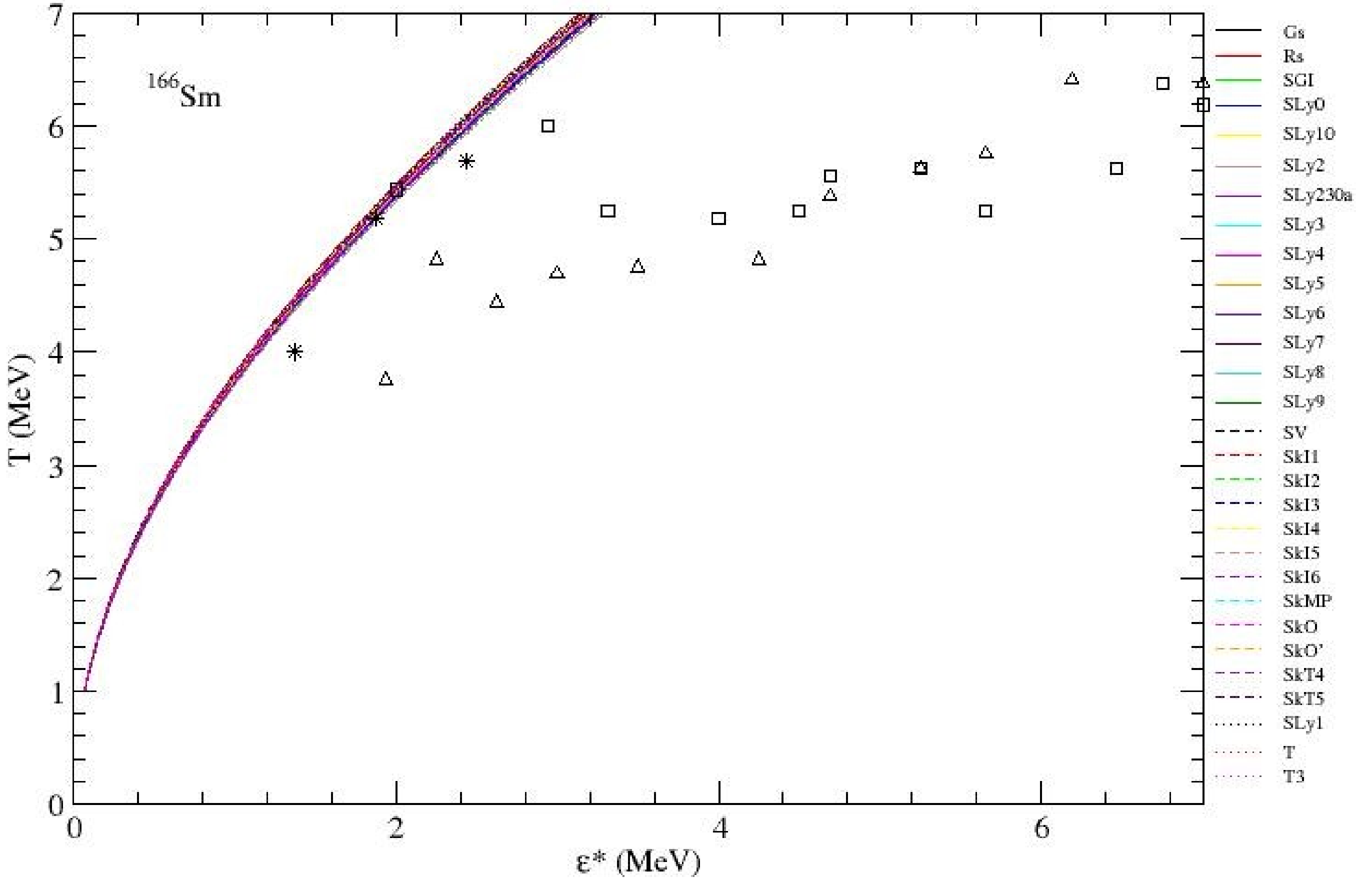

Walecka
NL2
NLSH
NL3
NL1
T/T_c
ρ/ρ_c
0.001
0.01
0.1



$K(T) = 9 \frac{\partial p}{\partial \rho}\Big|_{\rho_B}$
K/K(0)
T/T$_c$
Walecka
NL1
NL2
NL3
NLSH
Stöcker
0
0.2
0.4
0.6
0.8
1



J. B. Silva, *et al*, PLB 664 246 (2008).



$$\varepsilon^* = \min[\varepsilon(T,y,\rho)] - \min[\varepsilon(0,y,\rho)]$$

Limite não-relativístico

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - M)\psi + \frac{1}{2}{G_s}^2(\bar{\psi}\psi)^2 - \frac{1}{2}{G_V}^2(\bar{\psi}\gamma^\mu\psi)^2 + \frac{1}{3}A(\bar{\psi}\psi)^3 + \frac{1}{4}B(\bar{\psi}\psi)^4.$$

$$\downarrow$$

$$\mathcal{E} = c_1\rho^2 + c_2\rho^3 + c_3\rho^4 + c_4(\rho)\frac{3}{40}\left(\frac{6\pi^2}{\gamma}\right)^{2/3}\rho^{8/3} + \frac{3}{10M}\left(\frac{6\pi^2}{\gamma}\right)^{2/3}\rho^{5/3};$$

$$c_1 = {G_V}^2 - {G_s}^2, \qquad c_2 = -A, \qquad c_3 = -B \qquad \text{e} \qquad c_4(\rho) = \frac{4}{M^2}({G_s}^2 + 2A\rho + 3B\rho^2)$$

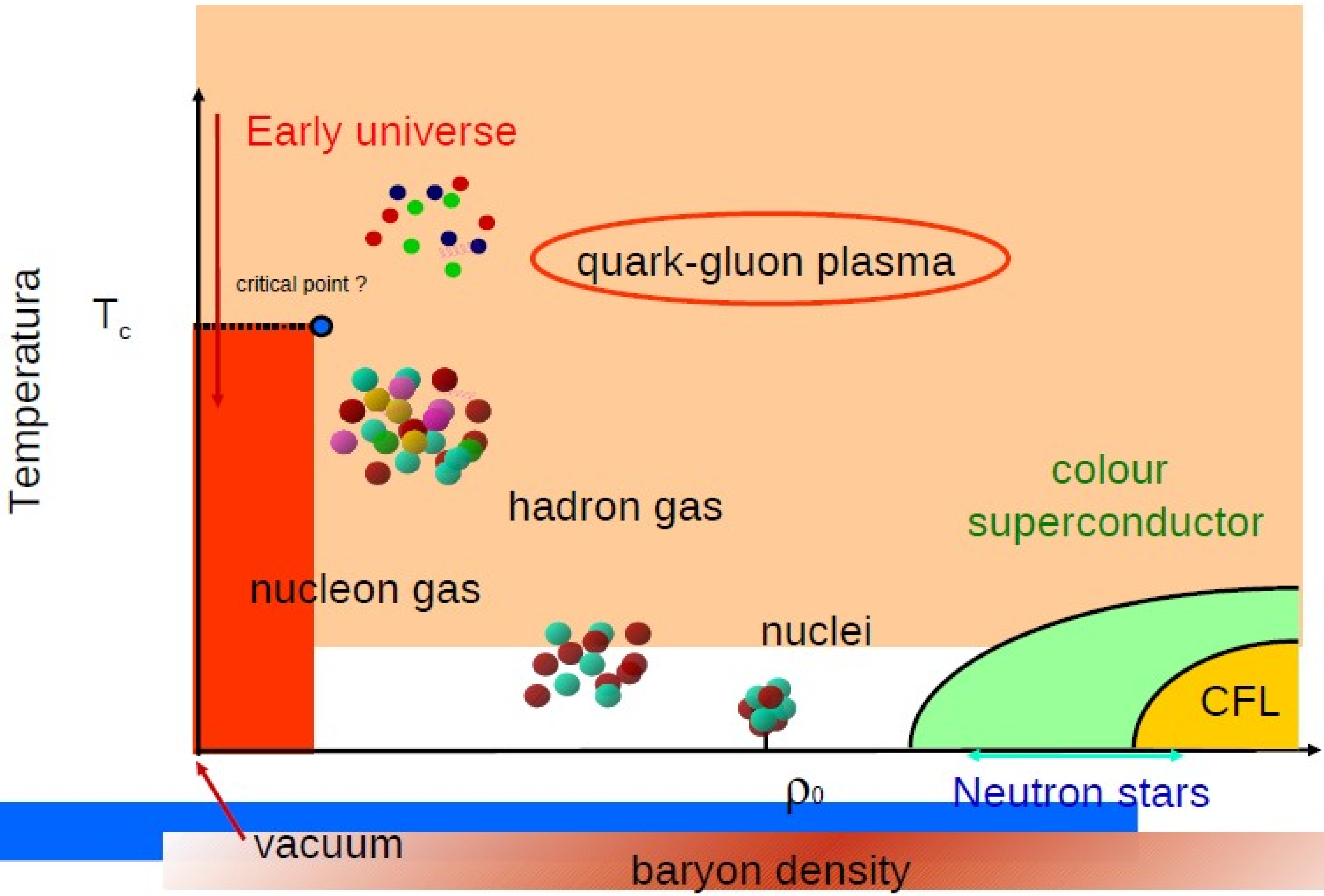
Conexão com modelos de Skyrme !

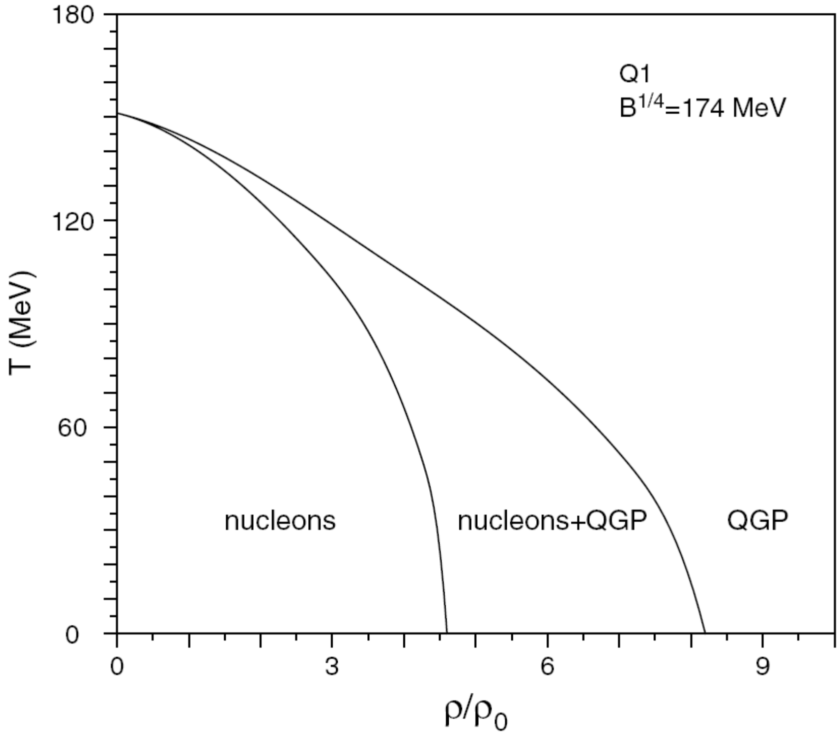
Por que Colidir Íons Pesados a energias Relativísticas?

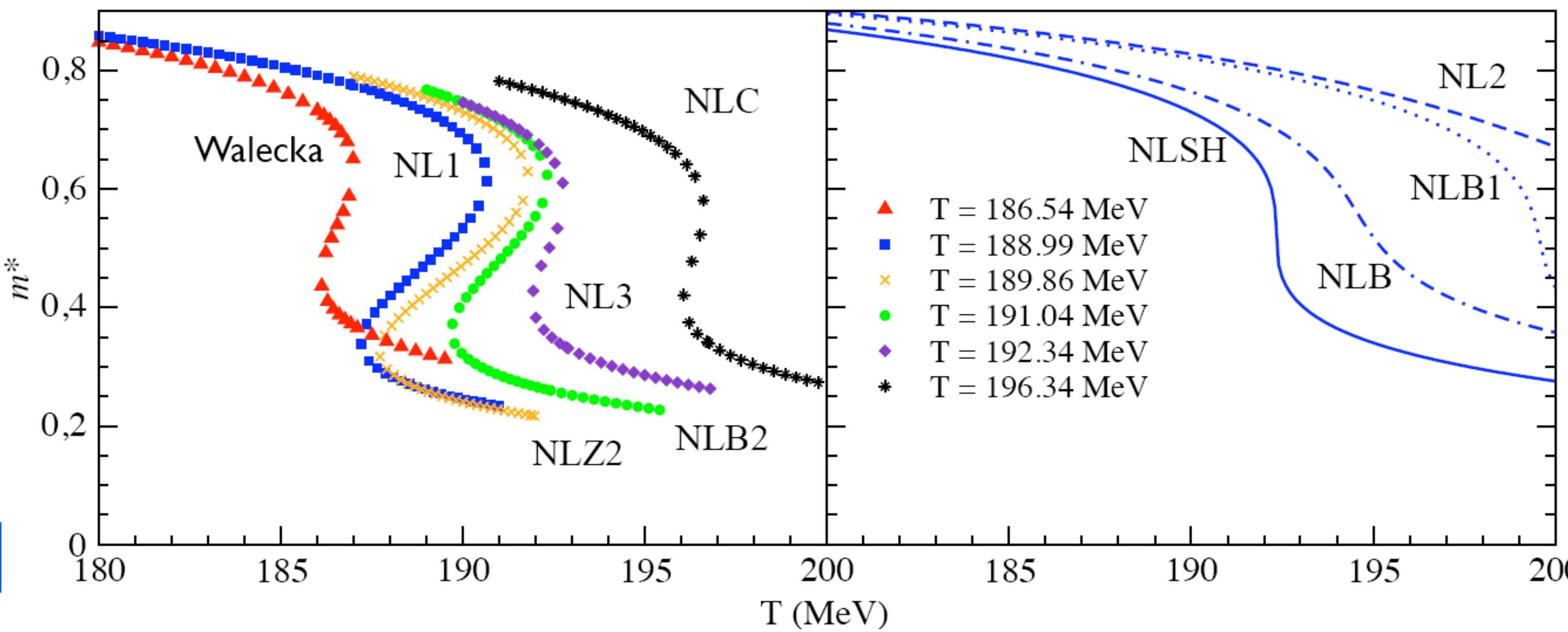
- **Estudo do diagrama de fase da matéria nuclear**
  - *Quark-Gluon Plasma*:***"A locally thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes."***
  - **Portanto, precisamos de um sistema denso (em termos de energia), grande e que atinja o equilíbrio térmico...**

V – Matéria Nuclear Muito Quente

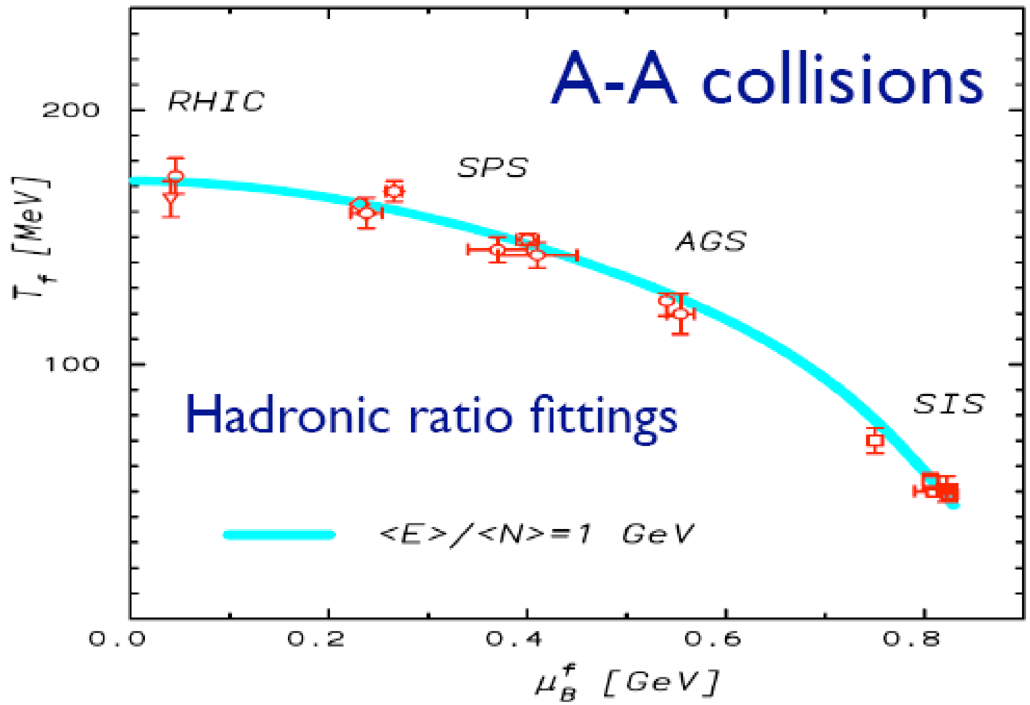
Diagrama de fase da QCD




Q1
B^1/4=174 MeV
nucleons
nucleons+QGP
QGP
T (MeV)
ρ/ρ0


Walecka
NL1
NLC
NL3
NLZ2
NLB2
NL2
NLSH
NLB1
NLB
T = 186.54 MeV
T = 188.99 MeV
T = 189.86 MeV
T = 191.04 MeV
T = 192.34 MeV
T = 196.34 MeV
m*
T (MeV)

Previous works



extracted from:

P. B. Munzinger, K. Redlich, J. Stachel, arXiv:nucl-th/0304013v1

$$\frac{\langle E\rangle}{\langle N\rangle} \simeq \langle m\rangle + \frac{3}{2}\,T$$

J. Cleymans and K. Redlich, PRL 81 (1998) 5284.

- Beam energy up to 100 *GeV/A : 19.6, 62.4, 130, 200 GeV/A*;
- Two independent rings (asymmetric beam collisions are possible);
- Beam species: from proton to *Au: Au+Au, p+p, d+Au,Cu+Cu*;
- Six interaction points: STAR, PHENIX, PHOBOS and BRAHMS

A Física de Íons Pesados Relativísticos.

- Existe equilíbrio químico?
- Uma grande produção de mésons.
- Uma grande produção de partículas estranhas.
- Razões anti-bárions/bárions grandes.
- Bons ajustes por modelos térmicos.

Modelos Térmicos

Temperature   Chemical Potential

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3}\int d^3p\left[e^{\sqrt{p^2+m_j^2}/T+\mu\cdot q_j/T}\pm 1\right]^{-1}$$

Yield   Mass   Quantum Numbers

Hagedorn, Becattini, Braun-Munzinger, Cleymans, Letessier, Mekijan,Rafelski, Redlich,Stachel, Tounsi

$$V\sum_i n_i B_i = Q_B = Z+N,$$

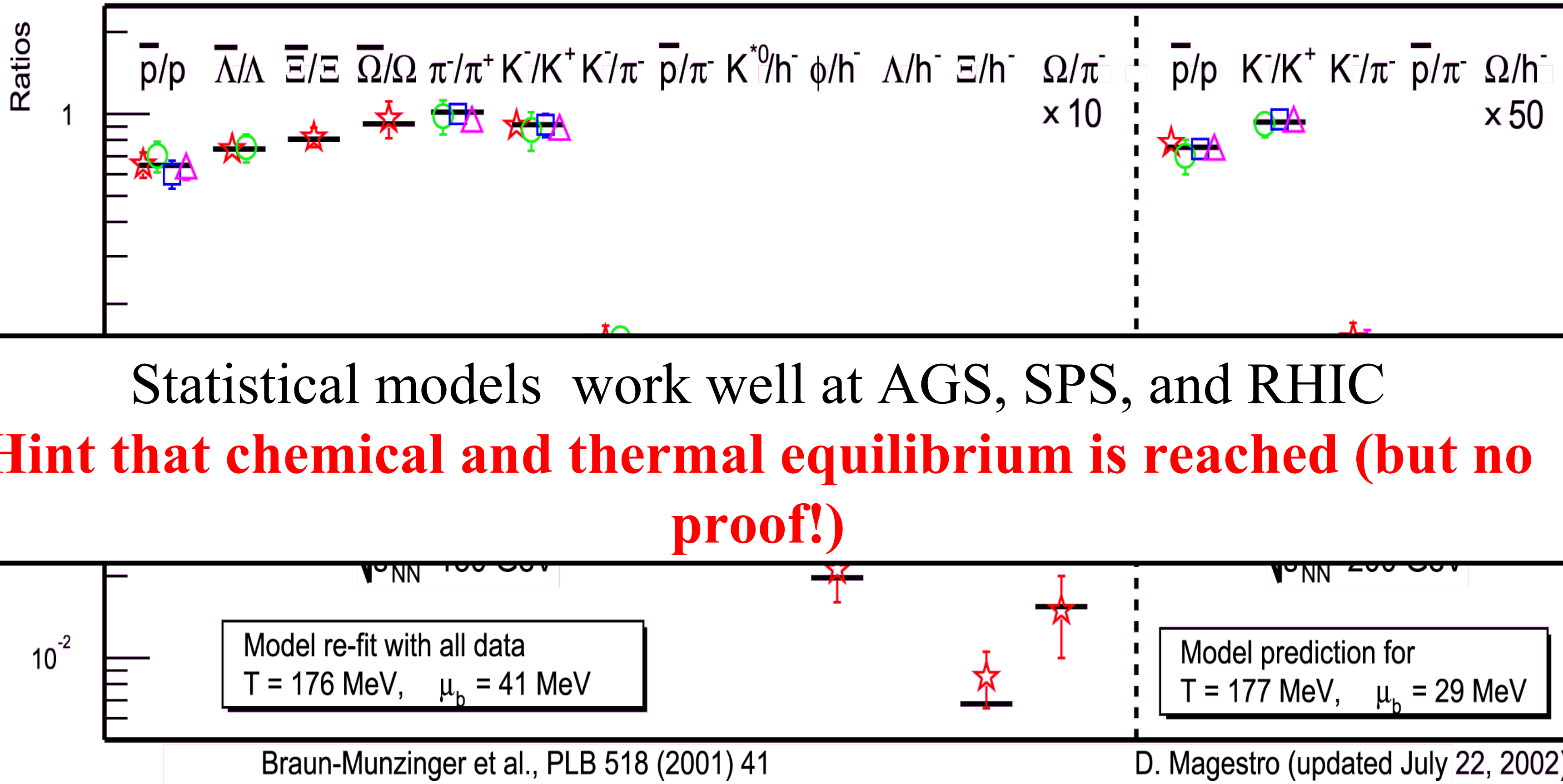
$$V\sum_i n_i S_i = Q_S = 0,$$

$$V\sum_i n_i I_{3i} = Q_{I_3} = (Z-N)/2,$$

→ **Conservation laws**

Assume: Ideal hadron resonance gas thermally and chemically equilibrated
Recipe: grand canonical ⇒partition function ⇒density of particles of species *j*
Input: measured particle ratios
Output: temperature T and baryon-chemical potential μ_B

Modelos Térmicos



Statistical models work well at AGS, SPS, and RHIC

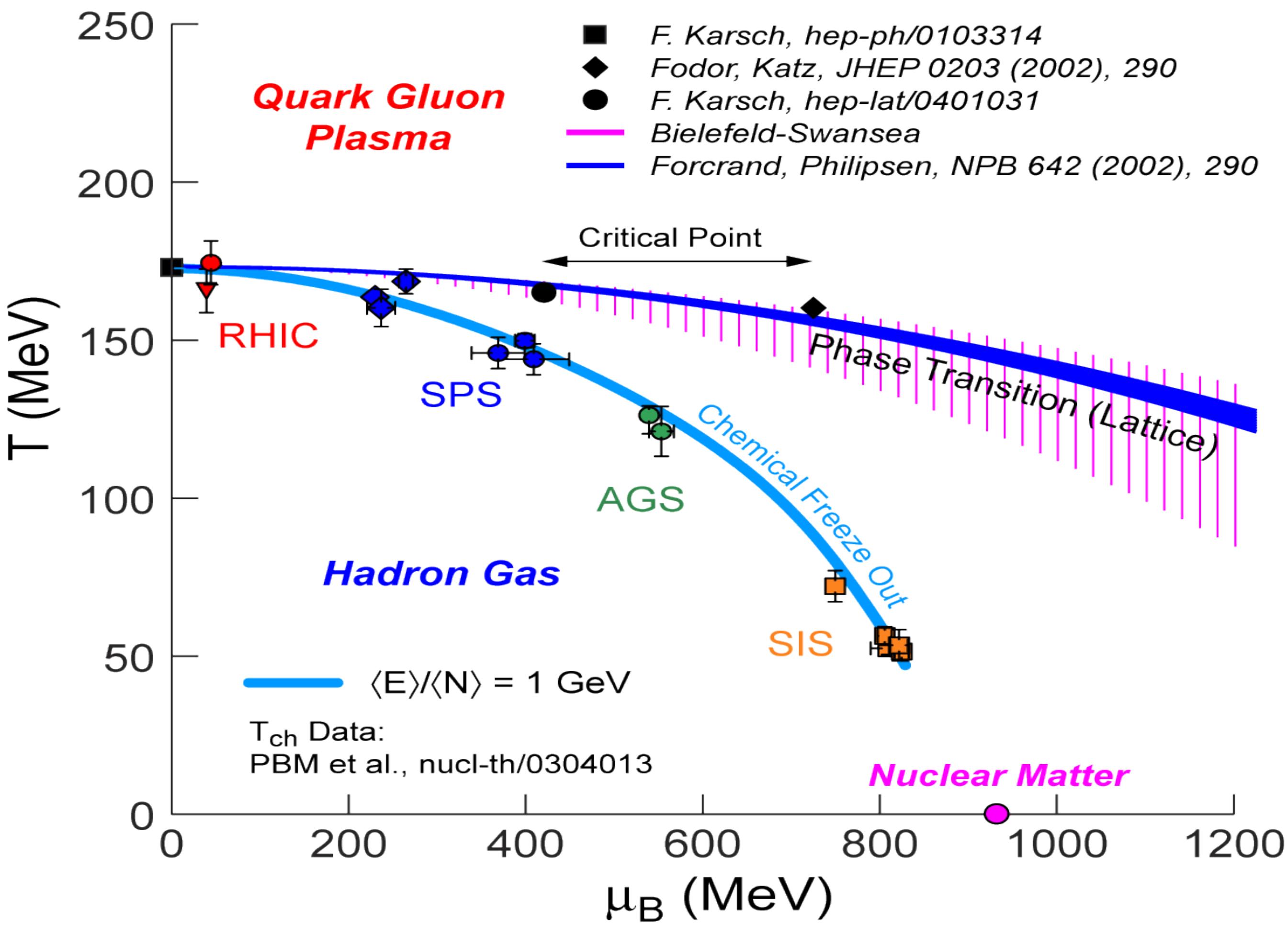
Hint that chemical and thermal equilibrium is reached (but no proof!)

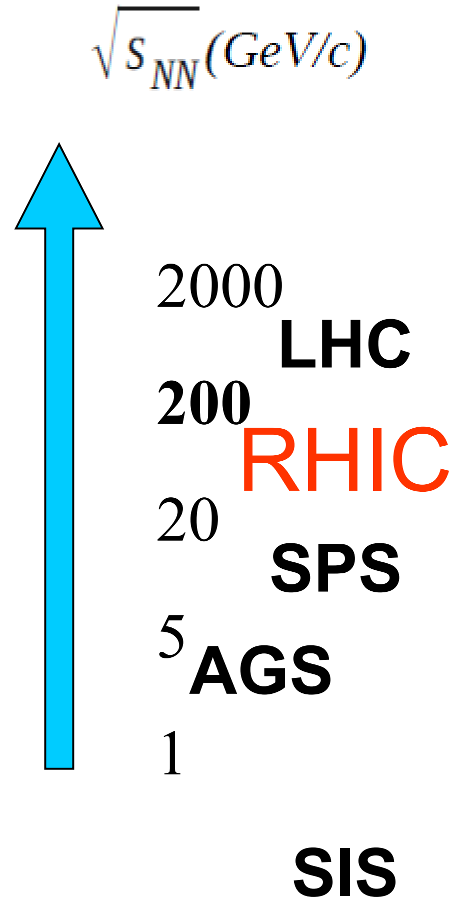
TABLE I: Particle ratios: experimental vs those obtained by relativistic mean field models. The last two columns refer to models with noninteracting particles.

Ratio	Exp. data	Exp.	NL3 [7]	TM1 [8]	GM1 [9]	GM3 [9]	TW [3]	DDME1 [5]	Octet	Octet+decuplet
$\bar{p}/p$	0.65 ± 0.07	STAR	0.650	0.646	0.626	0.597	0.656	0.663	0.661	0.649
	0.64 ± 0.07	PHENIX								
	0.60 ± 0.07	PHOBOS								
	0.64 ± 0.07	BRAHMS								
$\bar{p}/\pi^-$	0.08 ± 0.01	STAR	0.075	0.072	0.072	0.063	0.076	0.074	0.039	0.041
π^-/π^+	1.00 ± 0.02	PHOBOS	0.998	0.991	0.999	1.00	1.01	1.01	1.00	1.01
	0.95 ± 0.06	BRAHMS								
K^-/K^+	0.88 ± 0.05	STAR	0.912	0.911	0.907	0.905	0.896	0.900	0.961	0.941
	0.78 ± 0.13	PHENIX								
	0.91 ± 0.09	PHOBOS								
	0.89 ± 0.07	BRAHMS								
K^-/π^-	0.149 ± 0.02	STAR	0.234	0.234	0.242	0.243	0.228	0.227	0.232	0.235
$\bar{\Lambda}/\Lambda$	0.77 ± 0.07	STAR	0.681	0.680	0.666	0.644	0.663	0.675	0.687	0.689
$\bar{\Xi}^-/\Xi^-$	0.82 ± 0.08	STAR	0.746	0.747	0.735	0.711	0.739	0.748	0.714	0.732
K^{0*}/h^-	0.06 ± 0.017	STAR	0.058	0.059	0.063	0.064	0.064	0.063	0.060	0.061
$\bar{K}^{0*}/h^-$	0.058 ± 0.017	STAR	0.053	0.054	0.057	0.058	0.056	0.056	0.057	0.057
$\bar{\Omega}/\Omega$			0.693	0.699	0.715	0.723	0.585	0.586	—	0.784
$\bar{\Omega}/\pi^-$			0.001	0.001	0.002	0.002	0.001	0.001	—	0.001
Λ/h^-			0.021	0.020	0.021	0.020	0.023	0.022	0.013	0.014
Ω/Ξ^-			0.172	0.178	0.195	0.211	0.173	0.174	—	0.250
λ/K^{0*}			0.351	0.341	0.331	0.301	0.363	0.353	0.226	0.228
$\bar{\Xi}^-/\Lambda$			0.226	0.226	0.227	0.221	0.296	0.295	0.241	0.222
$\bar{\Xi}^-/\bar{\Lambda}$			0.332	0.332	0.341	0.343	0.330	0.327	0.312	0.322
$\Xi^-/\bar{K}^-$			0.047	0.045	0.050	0.049	0.048	0.045	0.027	0.030
$\bar{\Xi}^-/\bar{K}^-$			0.035	0.034	0.035	0.033	—	—	0.019	0.022
T (MeV)			149	149	152.0	152.8	146.6	146.2	146.4	148.8
μ_B (MeV)			47.5	46.5	47.5	48.0	62.8	57.0	30.5	32.5
$\rho \times 10^{-3}$ (fm^{-3})			8.37	8.03	9.62	9.95	4.90	4.45	2.41	4.77
χ^2			23.94	24.43	27.99	33.19	22.18	21.83	45.44	41.63
Radius (fm)			22.4	22.7	21.38	21.14	26.77	27.65	33.91	27.02

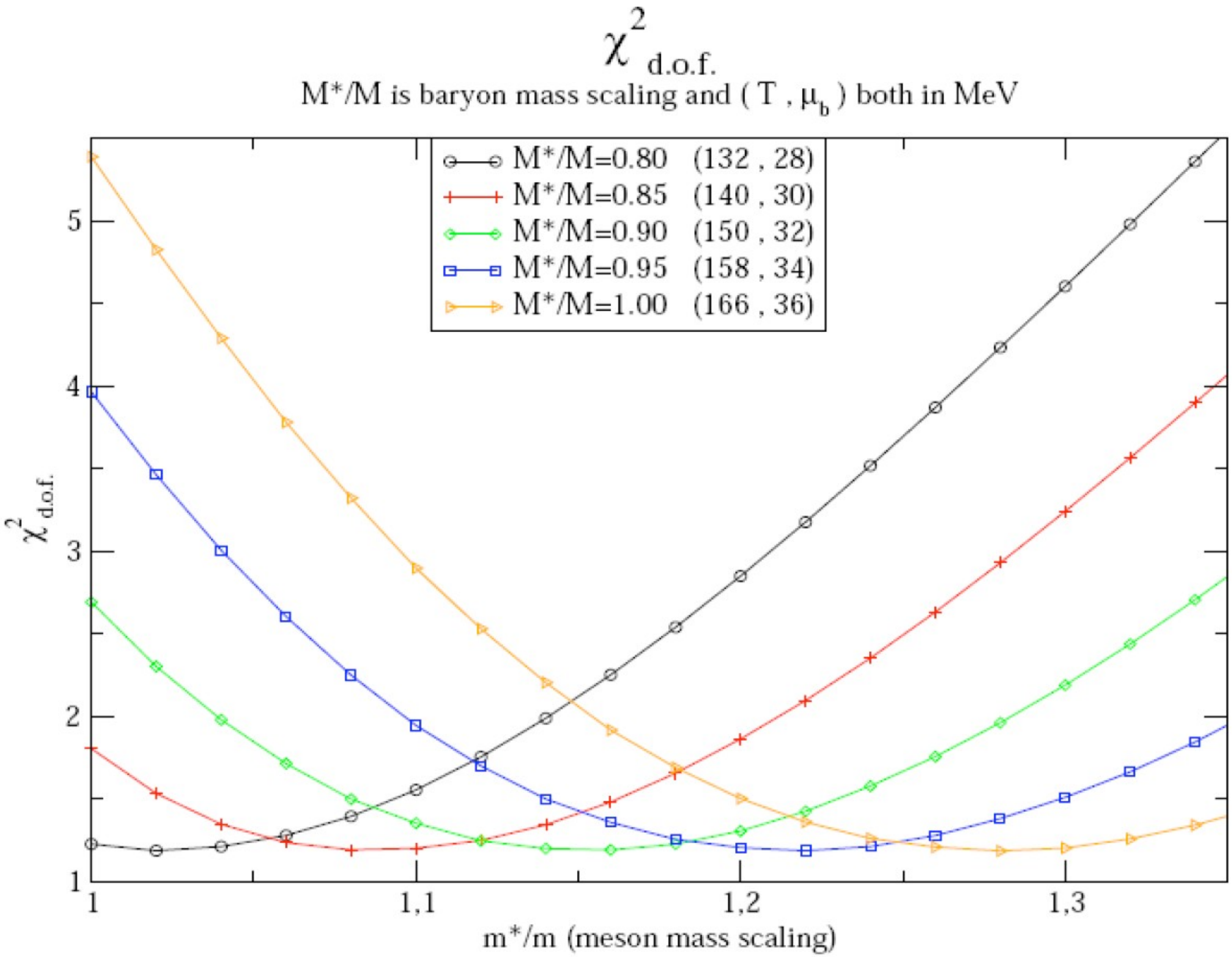
D. P. Menezes, et al, PRC 76 064902 (2007).

O Diagrama de fase





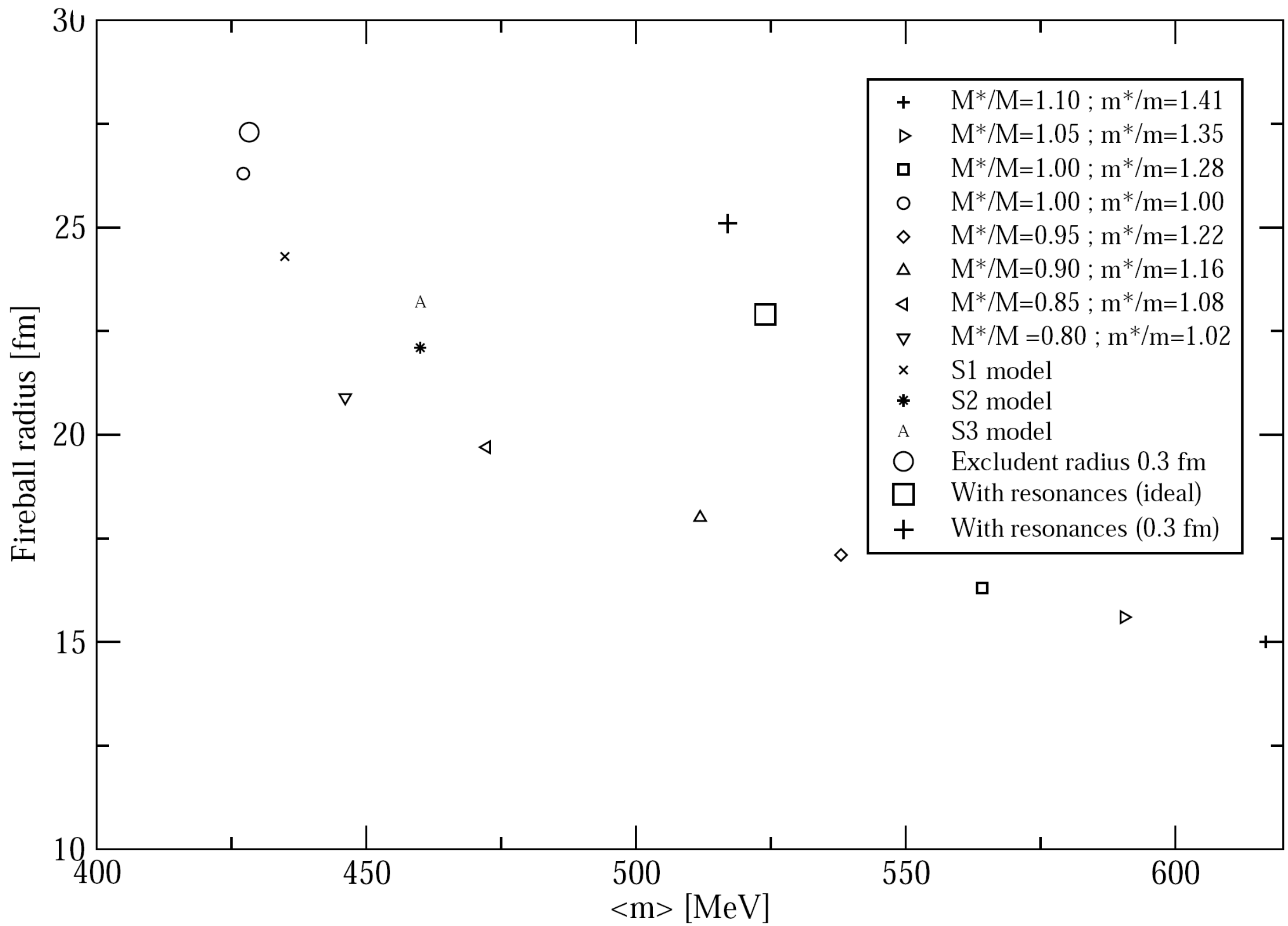
Mass scaling fittings



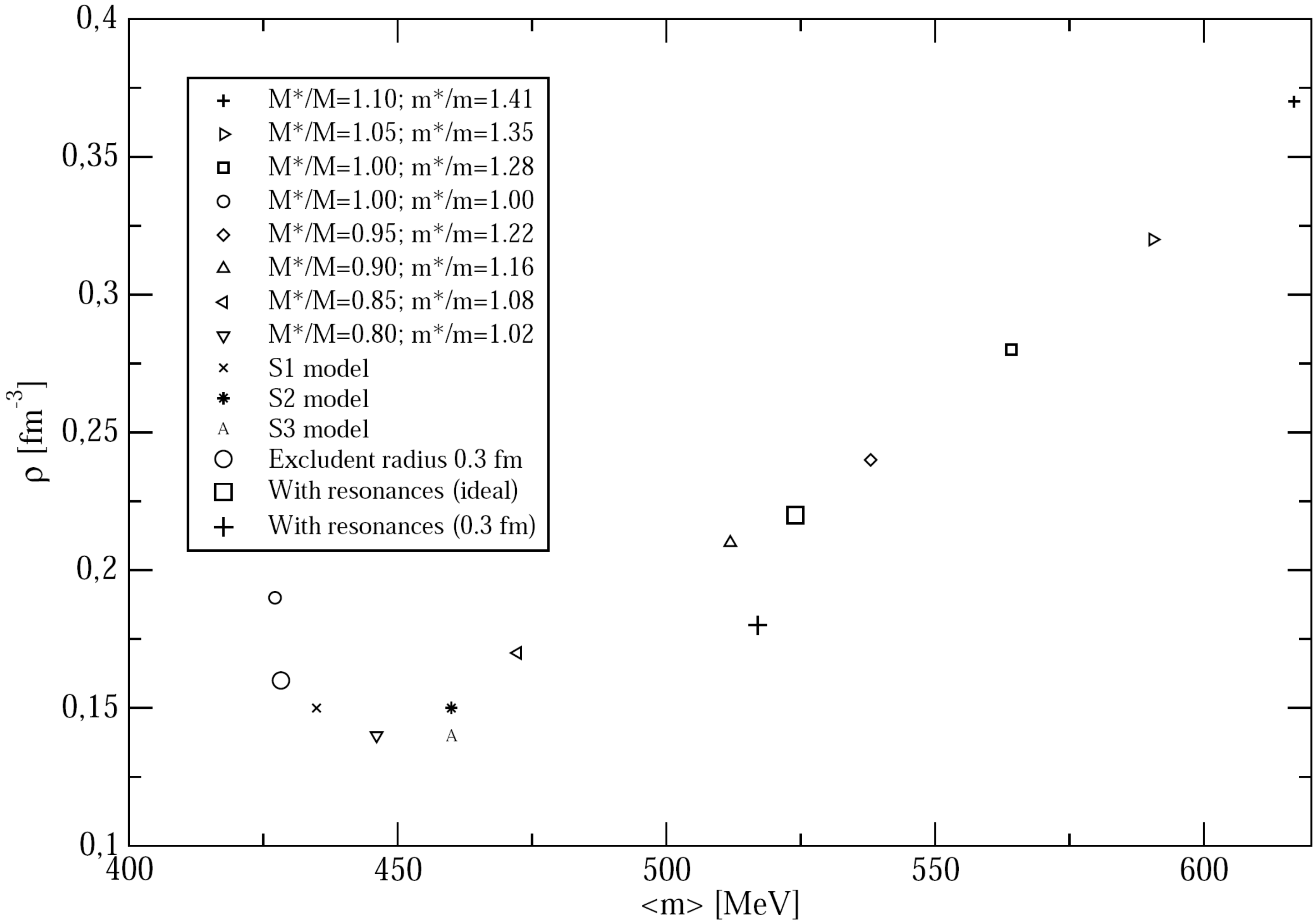
M^*/M	m^*/m	χ^2_{dof}	T	μ_B	μ_S	ε/P	ε/T^4	s/T^3	ε/ρ	R_{FB}	ρ	$<m>$
1.00	1.00	5.400	144	24	3.2	5.05	2.49	2.96	0.72	26.3	0.19	427.2
1.10	1.41	1.184	182	39	16.0	5.38	2.55	3.00	0.99	15.0	0.37	564.2
1.05	1.35	1.188	174	38	12.6	5.38	2.55	3.00	0.95	15.6	0.32	538.0
1.00	1.28	1.185	166	36	11.9	5.38	2.58	3.03	0.91	16.3	0.28	512.9
0.95	1.22	1.186	158	34	11.4	5.39	2.58	3.03	0.87	17.1	0.24	472.3
0.90	1.16	1.191	150	32	10.8	5.40	2.58	3.04	0.82	18.0	0.21	446.1
0.85	1.08	1.192	140	30	9.7	5.37	2.54	3.00	0.76	19.7	0.17	590.5
0.80	1.02	1.187	132	28	9.1	5.37	2.54	3.00	0.72	20.9	0.14	616.8
C1		0.78	171	48	11.1	6.43	6.27				0.66	
C2		0.77	153	51	9.4	6.39	4.53				0.35	
S3		1.37	136	24	9.4	5.22	2.37	2.28	0.72	24.3	0.14	434.9
S3A		0.72	140	26	4.6	5.29	2.23	2.64	0.75	22.1	0.15	460.0
S3B		0.54	138	25	9.3	5.32	2.17	2.56	0.74	23.2	0.14	460.0

Table 2: Some thermodynamics quantities obtained by own model. T, μ_B, μ_S are given in MeV. R_{FB} is given in fm. ρ is given in fm^{-3}. ε, P, s are energy density, pressure and entropy density. C1, C2 are taken from: PLB 547 (2002) 7. S3 are the Stocker masses without scaling. S3A (S3B) takes M*/M and m*/m from S3 but multiplies m*/m by 1.1 (1.075).

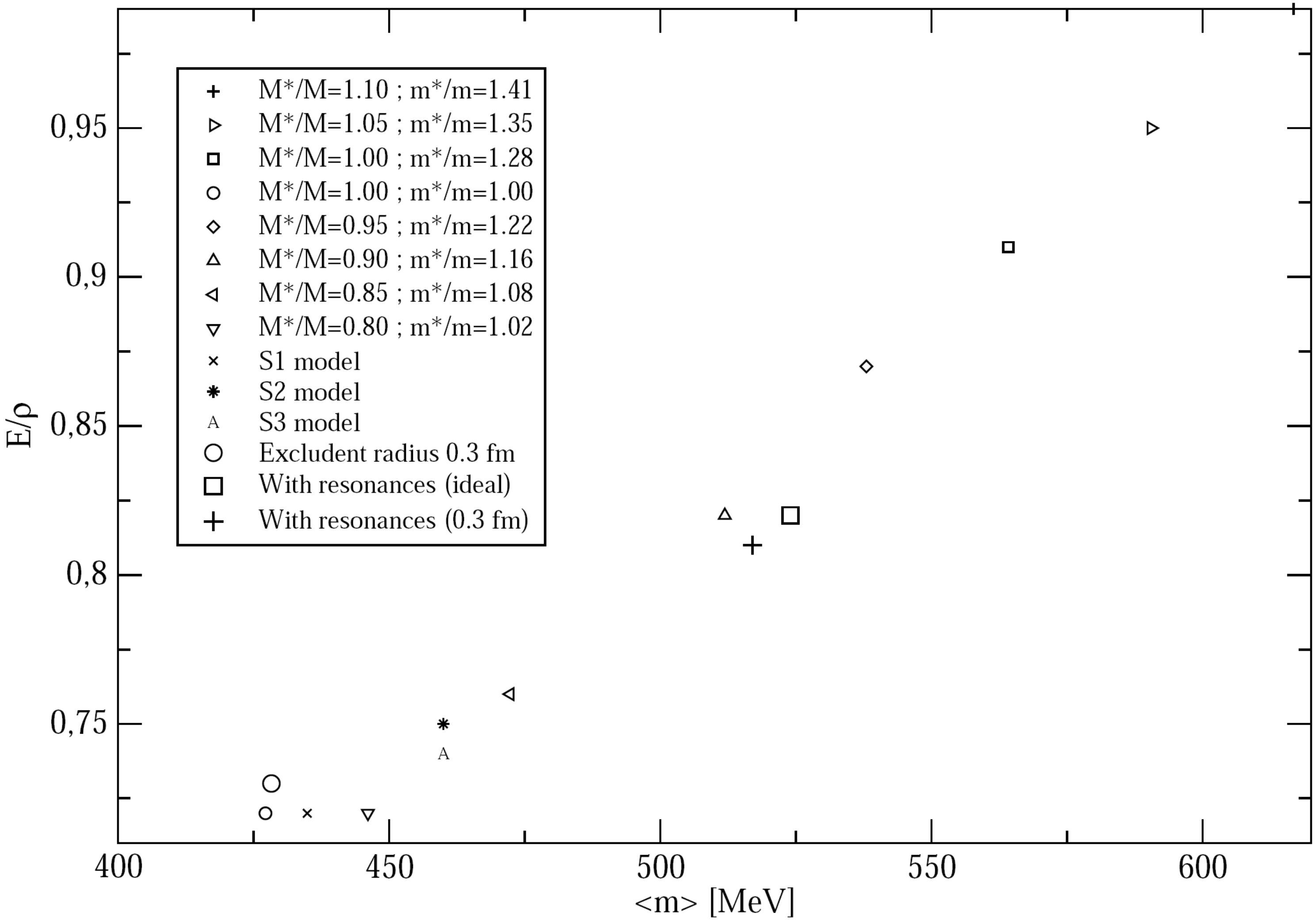
Fireball radius x Average Mass



ρ versus <m> for different models



E/ρ versus <m> for different models



Na Física dos Íons pesados e das Estrelas Compactas a matéria está em regimes bem diferentes.

Íons pesados (RHIC)	Estrelas de Nêutrons
Alta temperatura (T ~ 150 MeV).	Temperaturas baixas (T < 1MeV).
Baixas densidades.	Altas densidades ($\rho \sim 10\,\rho_o$).
Conservação da Estranheza.	Estranheza não é conservada.
Não há equilíbrio β.	Há equilíbrio β.
Os mésons dominam (π, K).	Os bárions dominam (nêutrons).
Sistema carregado.	Sistema neutro.


Explosão de Supernova