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The hyperon puzzle in Neutron Stars

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Neutron Stars: bulk properties

Mass	$M \sim 1.5\, M_\odot$
Radius	$R \sim 10$ km
Centr. Density	$\rho_c = (4 - 8)\, \rho_0$
Compactness	$R/R_g \sim 2 - 4$
Baryon number	$A \sim 10^{57}$
Binding energy	$B \sim 10^{53}$ erg

$B/A \sim 100$ MeV **$B/(Mc^2) \sim 10\%$**

Stellar structure:
General Relativity

Giant "atomic nucleus"
or "hypernucleus"
bound by gravity

$M_\odot = 1.989 \times 10^{33}$ g $R_\odot = 6.96 \times 10^5$ km $R_{g\odot} = 2.95$ km

$\rho_0 = 2.8 \times 10^{14}$ g/cm^3 (nuclear saturation density)

$R_g \equiv 2GM/c^2$ (Schwarzschild radius)

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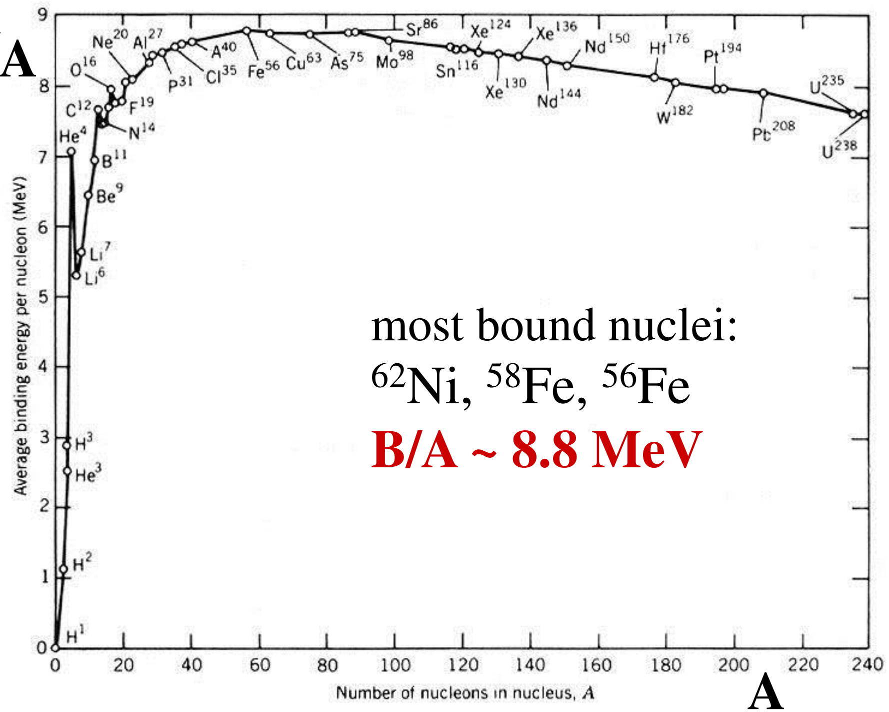
Atomic Nuclei: bulk properties

Mass number $A = 1 - 238$ (natural stable isotopes)

Radius $R = r_0 A^{1/3} \sim (2 - 10)$ fm

Density $\rho \sim \rho_0 = 2.8 \times 10^{14}$ g/cm^3

B/A



A

most bound nuclei:
^{62}Ni, ^{58}Fe, ^{56}Fe
B/A ~ 8.8 MeV

B/(Mc²)
~ (0.1–1) %

bound by nuclear interactions

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Relativistic equations for stellar structure

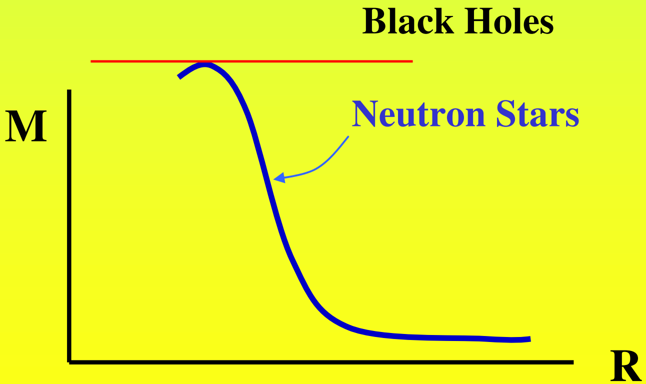
Tolman – Oppenheimer – Volkov equations (TOV)

$$\frac{dP}{dr} = -G\,\frac{m(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{c^2\rho(r)}\right)\left(1+4\pi\frac{r^3P(r)}{m(r)\,c^2}\right)\left[1-\frac{2Gm(r)}{c^2\,r}\right]^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2\rho(r)$$

$$\frac{d\Phi}{dr} = -\frac{1}{\rho(r)c^2}\frac{dP}{dr}\left(1+\frac{P(r)}{\rho(r)c^2}\right)^{-1}$$

One needs the **equation of state (EOS) of dense matter, P = P(ρ),** up to **very high densities**



$$\mathbf{M_{max}(EOS) \geq}$$ **all measured neutron star masses**

Two "heavy" Neutron Stars

PSR J1614–2230 $M_{NS} = 1.97 \pm 0.04\ M_\odot$

NS – WD binary system (He WD)

$M_{WD} = 0.5\ M_\odot$ (companion mass)

$P_b = 8.69$ hr (orbital period) $P = 3.15$ ms (PSR spin period)

$i = 89.17° \pm 0.02°$ (inclination angle)

P. Demorest et al., Nature 467 (2010) 1081

PSR J0348+0432 $M_{NS} = 2.01 \pm 0.04\ M_\odot$

NS – WD binary system

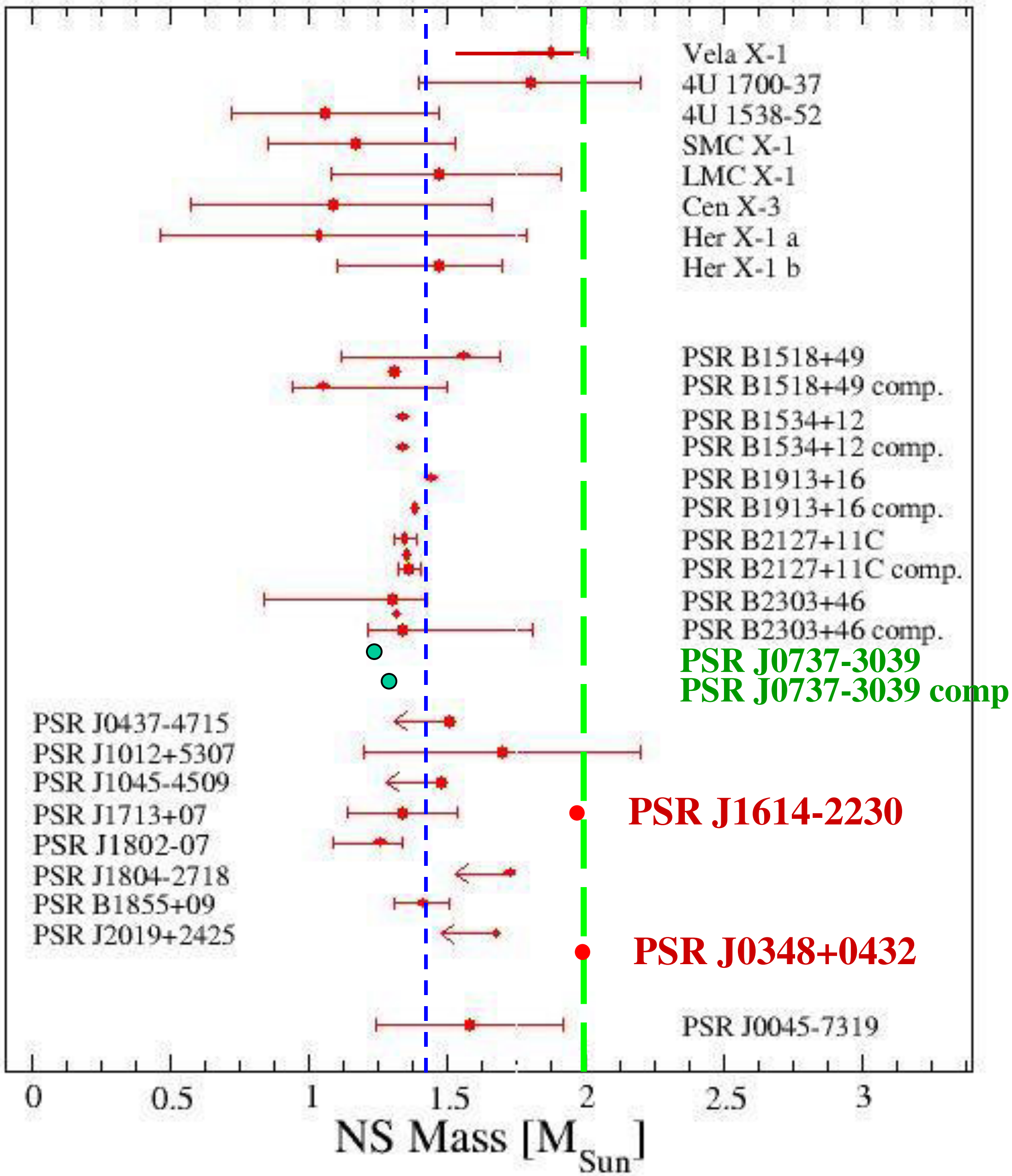
$M_{WD} = 0.172 \pm 0.003\ M_\odot$ (companion mass)

$P_b = 2.46$ hr (orbital period) $P = 39.12$ ms (PSR spin period)

$i = 40.2° \pm 0.6°$ (inclination angle)

Antoniadis et al., Science 340 (2013) 448

Measured Neutron Star Masses



$M_{max} \geq 2\, M_\odot$

Very stringent constraint on the EOS

soft EOS are ruled out

Neutron star physics in a nutshell

1) Gravity compresses matter at very high density

2) Pauli priciple

Stellar constituents are different species of **identical fermions** (n, p,….,e^-**,** μ^-)

⟶ antisymmetric wave function for particle exchange ➔ Pauli principle

Chemical potentials $\mu_n, \mu_p, \ldots \mu_e$ rapidly increasing functions of density

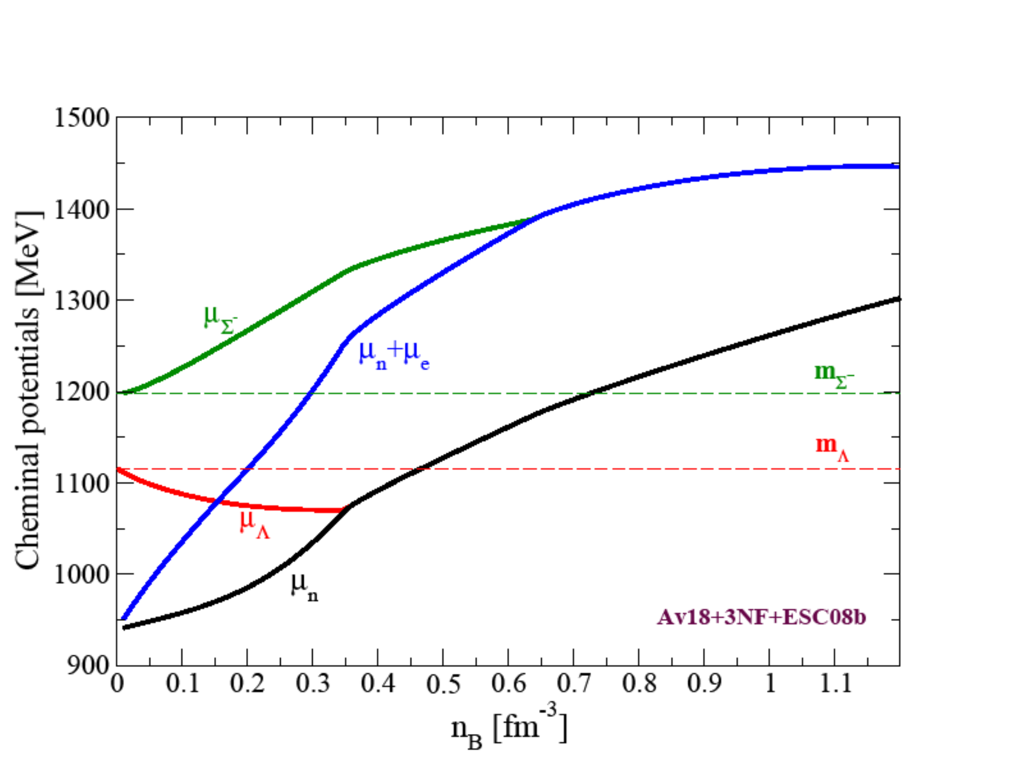
3) Weak interactions change the isospin and strangeness content of dense matter to minimize energy

Cold catalyzed matter (Harrison, Wakano, Wheeler, 1958)

The ground state (minimum energy per baryon) of a system of **hadrons** and **leptons** with respect to their mutual **strong** and **weak interactions** at a given total baryon density n and temperature T = 0.

Nucleon Stars [(n, p, e⁻, μ⁻)-matter] having

$M_{max}(EOS) \geq 2\,M_{\odot}$ ➡ $\rho_c\,(M_{max}) > \rho_{Y\text{-}thr}$



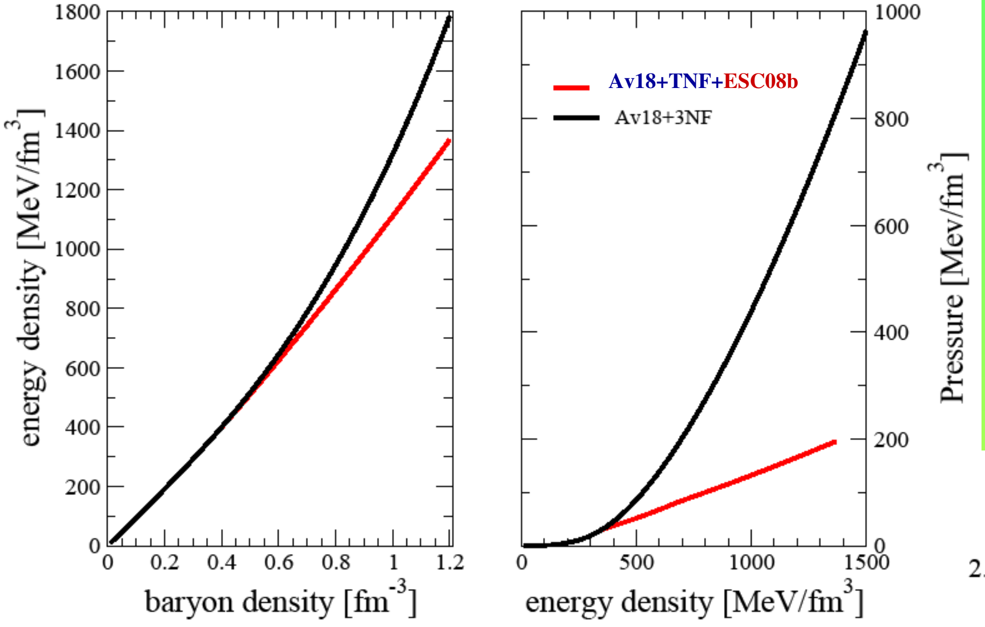
D. Logoteta, I. Bombaci (2014)

Hyperons appear in the stellar core above a threshold density

$$\rho_{Y\text{-}thr} \approx (2-3)\,\rho_0$$

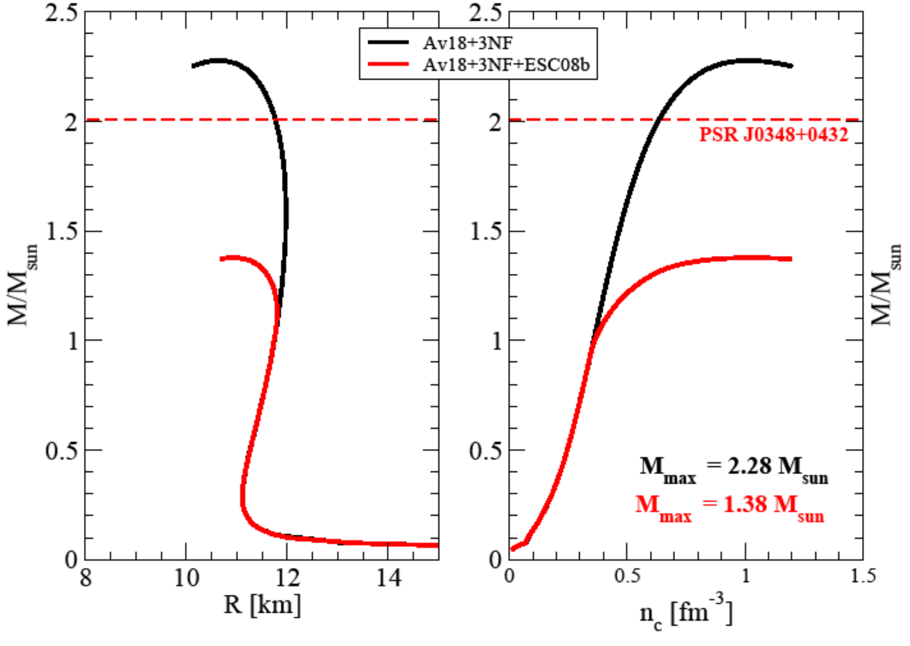
$$\mu_p = \mu_n - \mu_e = \mu_{\Sigma^+}$$
$$\mu_n = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_\Lambda$$
$$\mu_n + \mu_e = \mu_{\Sigma^-} = \mu_{\Xi^-}$$
$$\mu_\mu = \mu_e$$
$$n_p + n_{\Sigma^+} = n_e + n_\mu + n_{\Sigma^-} + n_{\Xi^-}$$

Equation of State of Hyperonic Matter



hyperons produce a strong softening of the EOS

Stellar mass



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D. Logoteta, I. Bombaci (2014)

The hyperon puzzle in Neutron Stars

Many hyperonic matter EOS models (mostly microscopic models) **predict the presence of hyperons in the NS core, but they give**

$$M_{max} < 2\, M_{\odot}$$

not compatible with measured NS masses

The hyperon puzzle in Neutron Stars

Many hyperonic matter EOS models (mostly microscopic models) **predict the presence of hyperons in the NS core, but they give**

$$M_{max} < 2\, M_{\odot}$$

not compatible with measured NS masses

A baffling problem which likely originates from our incomplete knowledge (model dependence) of the baryonic interactions.

Nucleon Stars

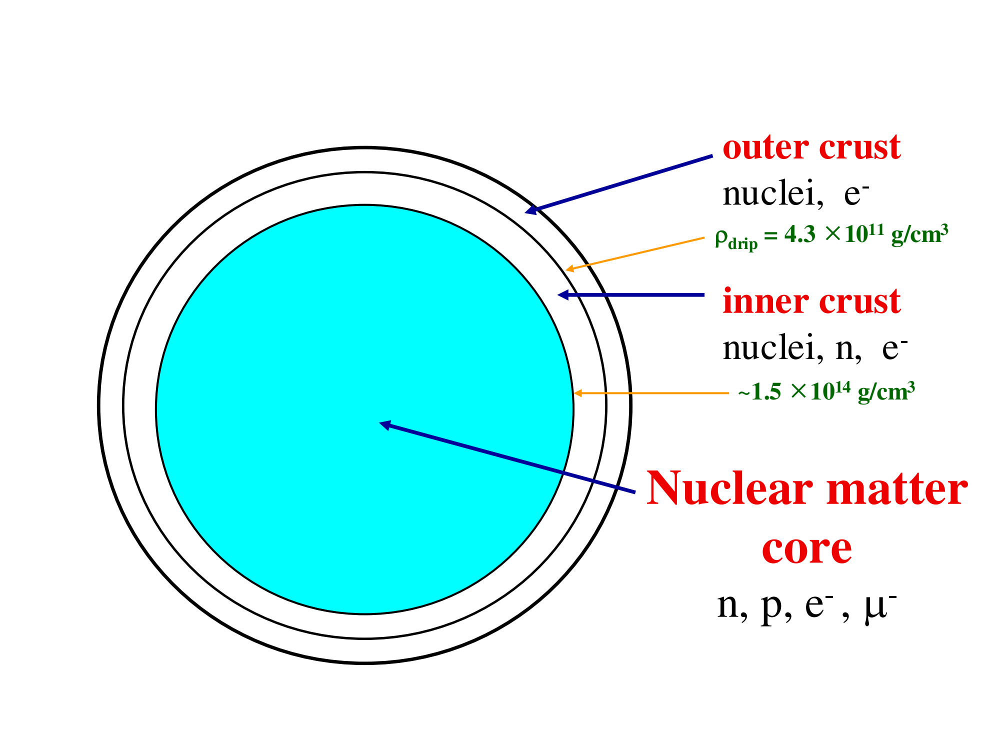
β-stable nuclear matter

$$p + e^- \leftrightarrow n + \nu_e$$

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

$$\mu_e \geq m_\mu$$

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



- **Equilibrium with respect to the weak interaction processes**

$$\mu_n - \mu_p = \mu_e$$

$$\mu_\mu = \mu_e$$

neutrino-free matter

$$\mu_\nu = \mu_{\bar{\nu}} = 0$$

- **Charge neutrality**

$$n_p = n_e + n_\mu$$

To be solved for any given value of the total baryon number density n_B

Microscopic approach to nuclear matter EOS

input

Two-body nuclear interactions: V_{NN}

"realistic" interactions: e.g. Argonne, Bonn, Nijmegen interactions.
Parameters **fitted to NN scatering data** with χ^2**/datum ~1**

Three-body nuclear interactions: V_{NNN}

semi-phenomenological. Parameters fitted to

- binding energy of **A = 3, 4** nuclei or
- empirical saturation point of symmetric nuclear matter: $\mathbf{n_0 = 0.16\ fm^{-3}}$ **, E/A = -16 MeV**

	AV18	AV18/UIX	Exp.
B(3H)	7.624	8.479	8.482
B(3He)	6.925	7.750	7.718
B(4He)	24.21	28.46	28.30

Values in MeV

Nuclear Matter at **n = 0.16 fm^{-3}**

E^{pot}(2BF)/A ~ -40 MeV

E^{pot}(3BF)/A ~ - 1 MeV

A. Kievsky, S. Rosati, M.Viviani, L.E. Marcucci, L. Girlanda, Jour. Phys.G 35 (2008) 063101
A. Kievsky, M.Viviani, L. Girlanda, L.E. Marcucci, Phys. Rev. C 81 (2010) 044003
Z.H. Li, U. Lombardo, H.-J. Schulze, W. Zuo, Phys. Rev. C 77 (2008) 034316

Microscopic EOS for nuclear matter:
Brueckner-Bethe-Goldstone theory

$$G_{\tau\tau'}(\omega) = V + V\sum_{k_a k_b}\frac{|k_a k_b\rangle Q_{\tau\tau'}\langle k_a k_b|}{\omega - e_\tau(k_a) - e_{\tau'}(k_b)}G_{\tau\tau'}(\omega)$$

$$e_\tau(k) = \frac{\hbar^2 k^2}{2m} + U_\tau(k)$$

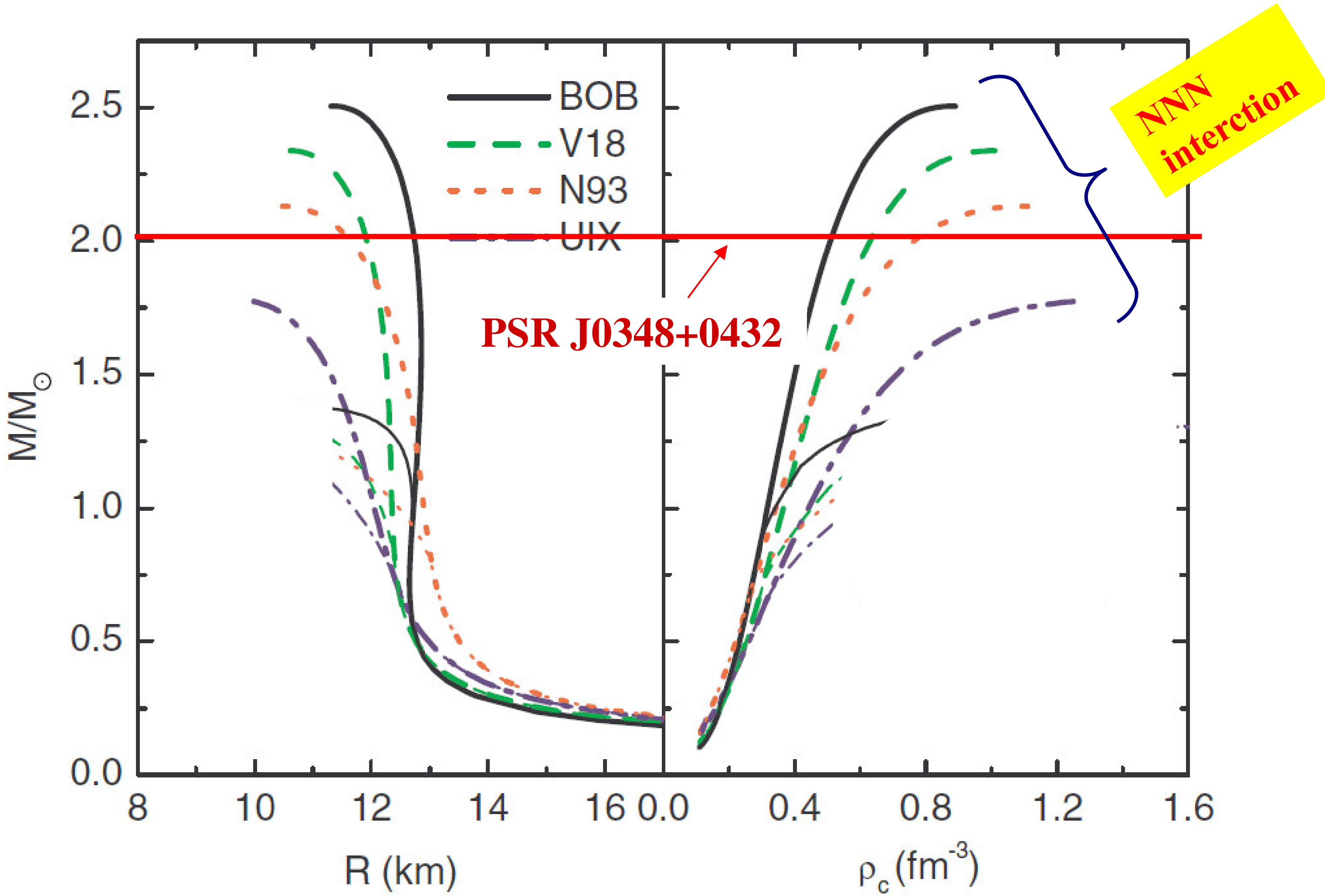
$$U_\tau(k) = \sum_{\tau'}\sum_{k'}\langle kk'|G_{\tau\tau'}(e_\tau(k) + e_{\tau'}(k'))|kk'\rangle_A$$

$$\tilde{E}(n_n, n_p) \equiv \frac{E}{A} = \frac{1}{A}\left\{\sum_\tau\sum_k\frac{\hbar^2 k^2}{2M} + \frac{1}{2}\sum_\tau\sum_k U_\tau(k)\right\}$$

$$n_n = \frac{1}{2}(1+\beta)n$$

$$n_p = \frac{1}{2}(1-\beta)n$$

Z.H. Li, H.-J. Schulze, PHYSICAL REVIEW C **78**, 028801 (2008)



$\rho_{Y\text{-}thr}$ depends on NNN interaction

Message taken from Nucleon Stars
(i.e. Neutron Stars with a pure nuclear matter core)

NN interactions are essential to have "large" stellar mass

For a free neutron gas $M_{max} = 0.71\ M_{\odot}$ **(Oppenheimer and Volkoff, 1939)**

NNN interactions are essential

(i) to reproduce the correct **empirical saturation point of nuclear matter**

(ii) to reproduce measured neutron star masses, i.e. to have $M_{max} > 2\ M_{\odot}$

Few-body ($A \leq 4$) nuclear systems properties and/or
the **saturation properties of nuclear matter** **can not constrain**
the **NNN interactions at high density**

models of **Nucleon Stars**

(i.e. Neutron Stars with a pure nuclear matter core)

are able to explain

measured Neutron Star masses

as those of

PSR J1614-2230 and PSR J0348+0432

$$M_{NS} \approx 2\, M_{\odot}$$

but the presence of hyperons in the star seems unavoidable:

hyperon puzzle problem

Microscopic approach to hyperonic matter EOS

input

2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)

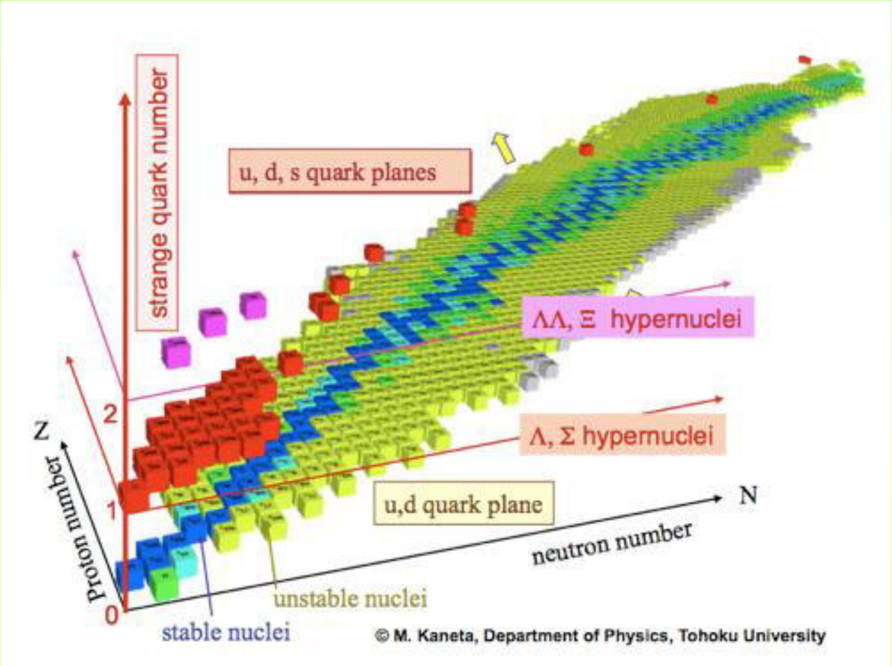
e.g. Nijmegen, Julich models

3BF: NNN, NNY, NYY, YYY

Hyperonic sector: experimental data

1. **YN scattering data ≈ 50**
   (NN data ≈ 4300)

2. **Hypernuclei : ≈ 40 $_{\Lambda}$X , ≈ 5 $_{\Lambda\Lambda}$X**
   (nuclei ≈ 3300)



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Microscopic EOS for hyperonic matter: extended Brueckner theory

$$G(\omega)_{B_1B_2B_3B_4} = V_{B_1B_2B_3B_4} + \sum_{B_5B_6} V_{B_1B_2B_5B_6} \frac{Q_{B_5B_6}}{\omega - e_{B_5} - e_{B_6}} G(\omega)_{B_5B_6B_3B_4}$$

$$e_{B_i}(k) = M_{B_i}c^2 + \frac{\hbar^2 k^2}{2M_{B_i}} + U_{B_i}(k)$$

$$U_{B_i}(k) = \sum_{B_j} \sum_{k' \le k_{F B_j}} \langle \vec{k}\vec{k}' | G_{B_iB_jB_iB_j}(\omega = e_{B_i} + e_{B_j}) | \vec{k}\vec{k}' \rangle$$

V is the **baryon -baryon interaction for the baryon octet**

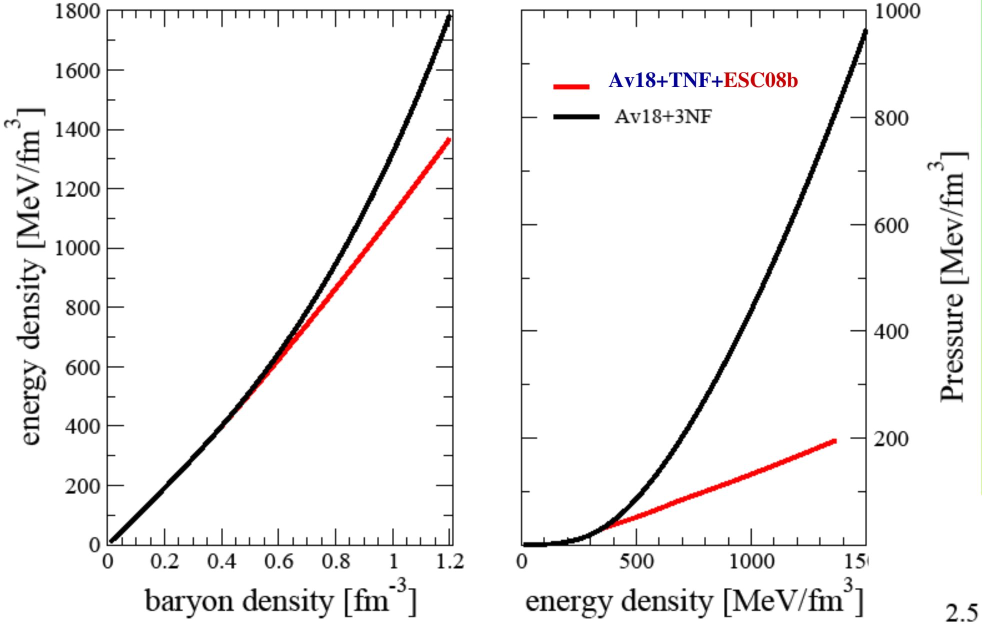
(n, p, Λ, Σ⁻, Σ⁰, Σ⁺, Ξ⁻, Ξ⁰)

- **Energy per baryon in the BHF approximation**

$$E/N_B = 2\sum_{B_i}\int_0^{k_F[B_i]} \frac{d^3k}{(2\pi)^3}\left\{ M_{B_i}c^2 + \frac{\hbar^2k^2}{2M_{B_i}} + \frac{1}{2}U^N_{B_i}(k) + \frac{1}{2}U^Y_{B_i}(k)\right\}$$

Baldo, Burgio, Schulze, Phys.Rev. C61 (2000) 055801;
Vidaña, Polls, Ramos, Engvik, Hjorth-Jensen, Phys.Rev. C62 (2000) 035801;
Vidaña, Bombaci, Polls, Ramos, Astron. Astrophys. 399, (2003) 687.

Equation of State of Hyperonic Matter

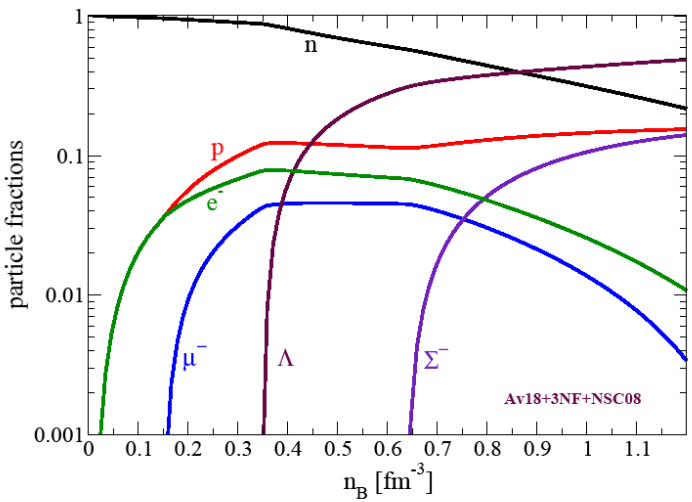


BHF
Av18 + TNF + ESC08b
no hyperonic TBF

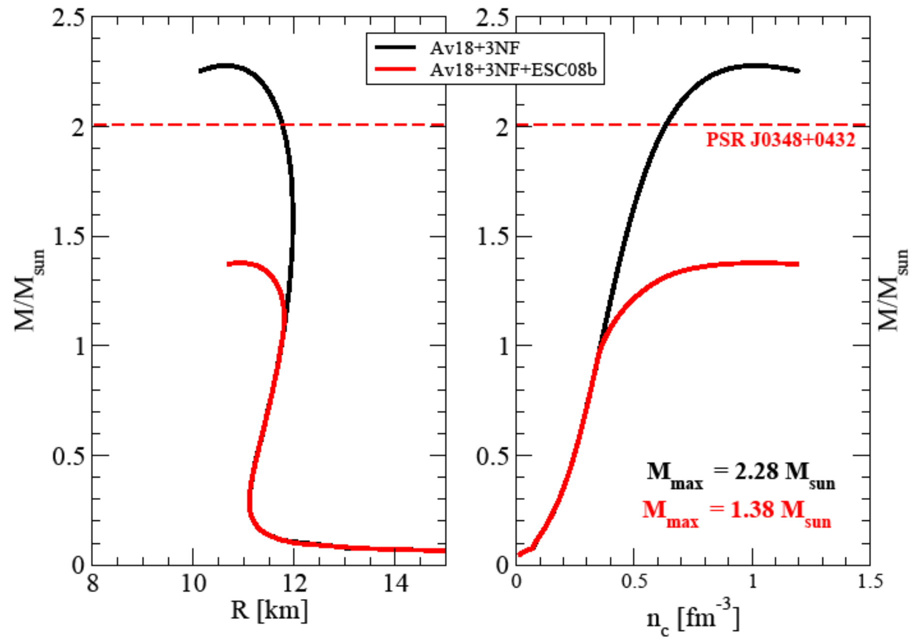
D. Logoteta, I. Bombaci (2014)

TNF: Z H.. Li, U. Lombardo, H.-J. Schulze. W. Zuo, Phys. Rev. C 77 (2008)

Particle fractions



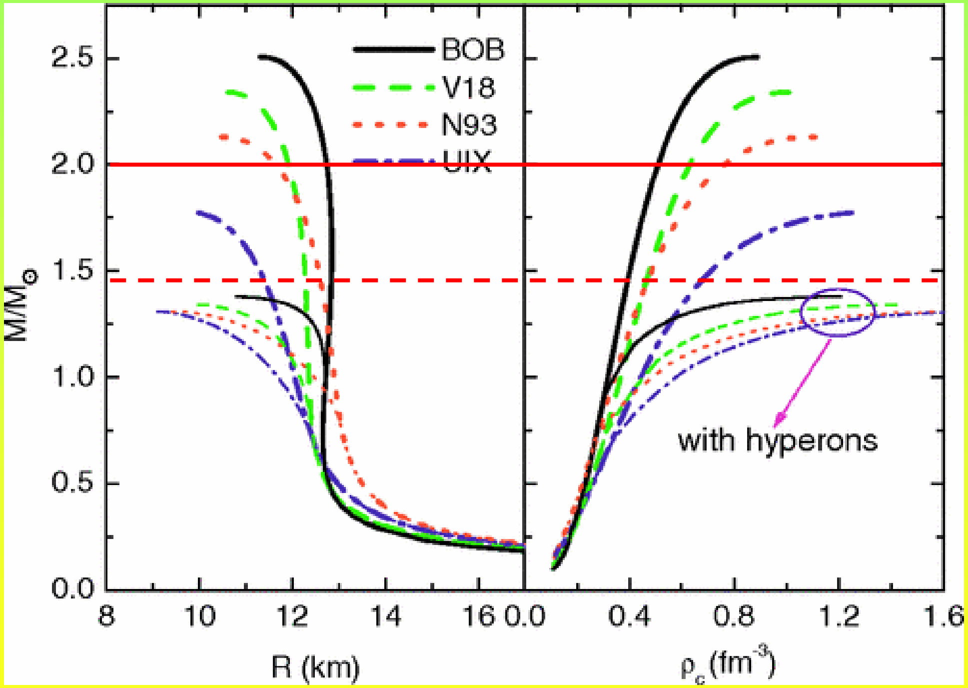
Stellar mass



The stellar mass-radius relation

NN + NNN + NY(NSC89)

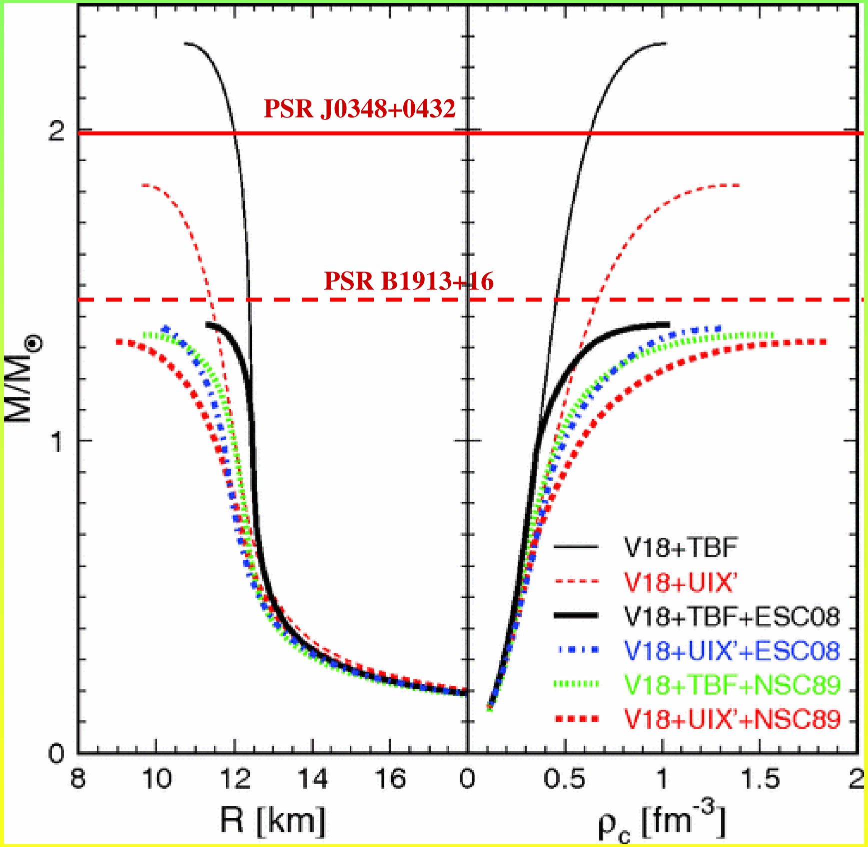
no hyperonic TBF



Z. H. Li, H.-J. Schulze, Phys. Rev. C 78 (2008) 028801

NN(Av18) + NNN + NY(ESC08 or NSC89)

no hyperonic TBF



H.-J. Schulze, T. Rijken, Phys. Rev. C 84 (2011) 035801

Hyperons in Neutron Stars: implications for the stellar structure

The presence of hyperons reduces the maximum mass of neutron stars:

$$\Delta M_{max} \approx (0.5 - 1.2)\, M_{\odot}$$

Therefore, **to neglect hyperons always leads to an overstimate of the maximum mass of neutron stars**

hyperon puzzle

Microscopic EOS for hyperonic matter: "very soft" non compatible with measured NS masses

→

Need for extra pressure at high density

↔

Improved NY, YY two-body interaction

Three-body forces: NNY, NYY, YYY

↑

Need for new experimental data from hypernuclear physics

YN scattering
Topical session 9a on Thu

Hyperonic TBF as a possible solution of the hyperon puzzle in neutron stars

YNN three-body forces in hypernuclei

A. Gal, Phys. Rev. Lett. 18 (1967) 568
R. K. Bhaduri, B.A. Losieau, Y. Nogami, Ann. Phys. 44 (1967) 55
B.A. Losieau, Nucl. Phys. B 9 (1969) 169
A.R. Bodmer, Q.N. Usmani, J. Carlson, Phys. Rev. C29 (1984) 684

"Universal" three-body forces between nucleons and hyperons

S. Nishizaki, Y. Yamamoto, T. Takatsuka, Prog. Theor. Phys. 105 (2001) 607
S. Nishizaki, Y. Yamamoto, T. Takatsuka, Prog. Theor. Phys 108 (2002) 703
T. Takatsuka, Prog. Theor. Phys. Suppl. 156 (2004) 84
Y. Yamamoto, T. Furumoto, N. Yasutake, Th. Rijken, Phys. Rev. C 90, (2014) 045805

Yamamoto' s talk and Takatsuka's talk in this section

Estimation of the effect of hyperonic TBF on the maximum mass of neutron stars

I.Vidaña, D. Logoteta, C. Providencia, A. Polls, I. Bombaci, EPL 94 (2011) 11002

- ☆ **BHF calculations: NN (Av18) + NY (NSC89)**
- ☆ **TBF: phenomenological density dependent contact terms**

$$\varepsilon_3 = a_{NN} n_N^2 + b_{NN} n_N^{\gamma_{NN}+1}$$
$$+ a_{N\Lambda} n_N n_\Lambda + b_{N\Lambda} n_N n_\Lambda \frac{n_N^{\gamma_{N\Lambda}} + n_\Lambda^{\gamma_{N\Lambda}}}{n_N + n_\Lambda}$$
$$+ a_{N\Sigma} n_N n_\Sigma + b_{N\Sigma} n_N n_\Sigma \frac{n_N^{\gamma_{N\Sigma}} + n_\Sigma^{\gamma_{N\Sigma}}}{n_N + n_\Sigma}$$

Energy density form inspired by **S. Balberg, A. Gal, Nucl Phys. A 625, (1997) 435** we assume:

$$a_{N\Lambda} = a_{N\Sigma} \qquad b_{N\Lambda} = b_{N\Sigma} \qquad \gamma_{N\Lambda} = \gamma_{N\Sigma}$$

$$\frac{a_{NY}}{a_{NN}} = \frac{b_{NY}}{b_{NN}} \equiv x$$

empirical saturation point of symmetric NM

$$n_0 = 0.16 \ \ \mathrm{fm}^{-3}$$

$$\tilde{E}_0 = -16 \ \ \mathrm{MeV}$$

$$K_0 = 210 \div 285 \ \ \mathrm{MeV}$$

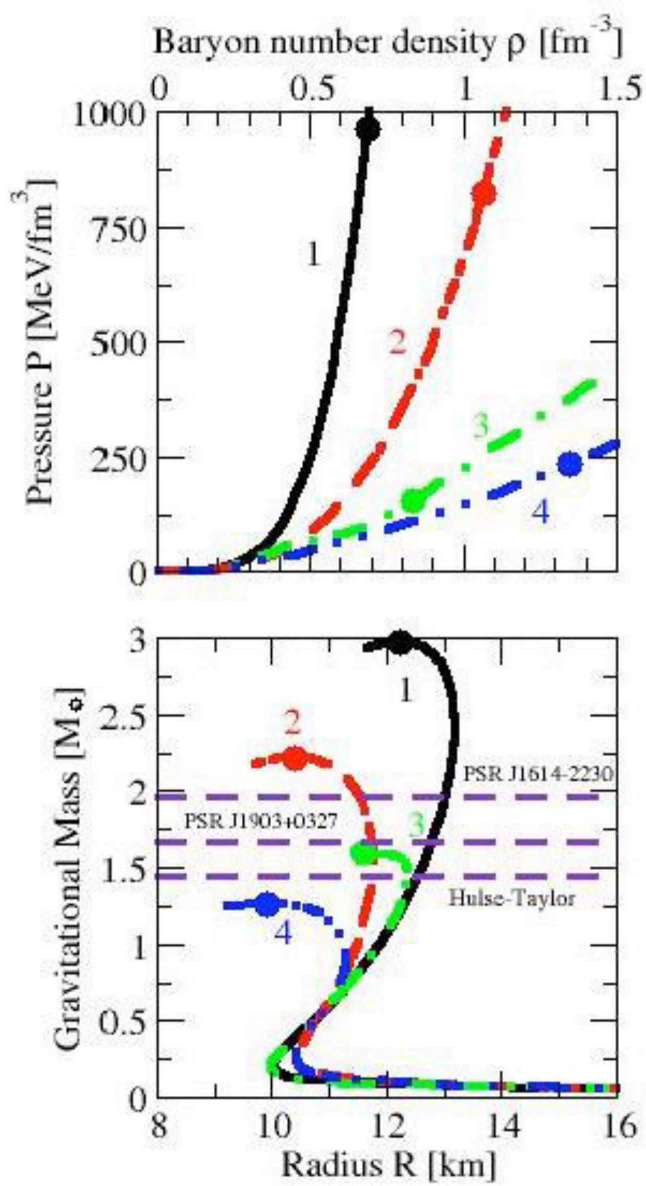
$\Longrightarrow$ $a_{NN}\ ,\ b_{NN}\ ,\ \gamma_{NN}$

Binding energy of Λ in NM

$$B_\Lambda = -28 \ \ \mathrm{MeV} = \mathrm{U}_\Lambda(k=0) + a_{NY} n_0 + b_{NY} n_0^{\gamma_{NY}}$$

$\Longrightarrow$ γ_{NY}

effect of hyperonic TBF on the maximum mass of neutron stars



γ_{NN}	x	γ_{YN}	Maximum Mass
	0	-	1.27 (2.22)
	1/3	1.49	1.33
2	2/3	1.69	1.38
	1	1.77	1.41
	0	-	1.29 (2.46)
	1/3	1.84	1.38
2.5	2/3	2.08	1.44
	1	2.19	1.48
	0	-	1.34 (2.72)
	1/3	2.23	1.45
3	2/3	2.49	1.50
	1	2.62	1.54
	0	-	1.38 (2.97)
	1/3	2.63	1.51
3.5	2/3	2.91	1.56
	1	3.05	1.60

I.Vidaña, D. Logoteta, C. Providencia, A. Polls, I. Bombaci, EPL 94 (2011) 11002

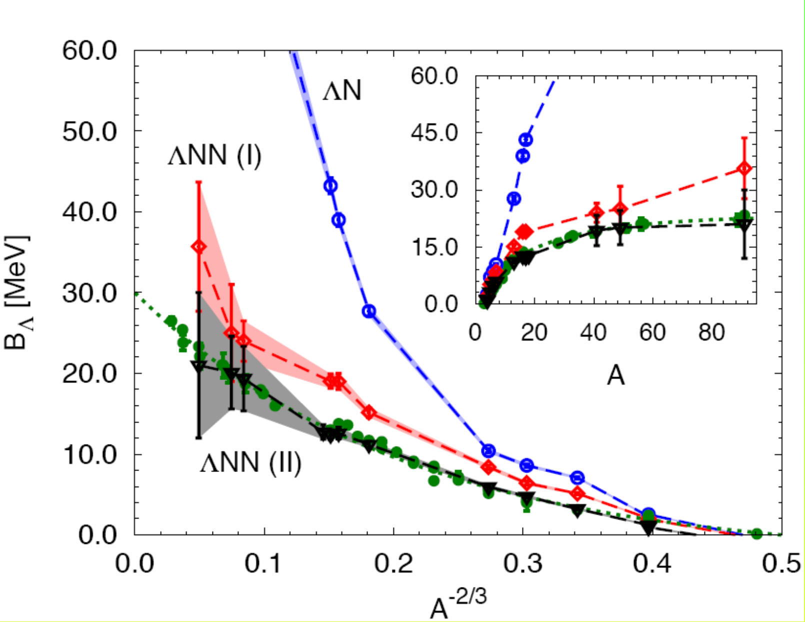
Miscroscopic hyperonic TBF

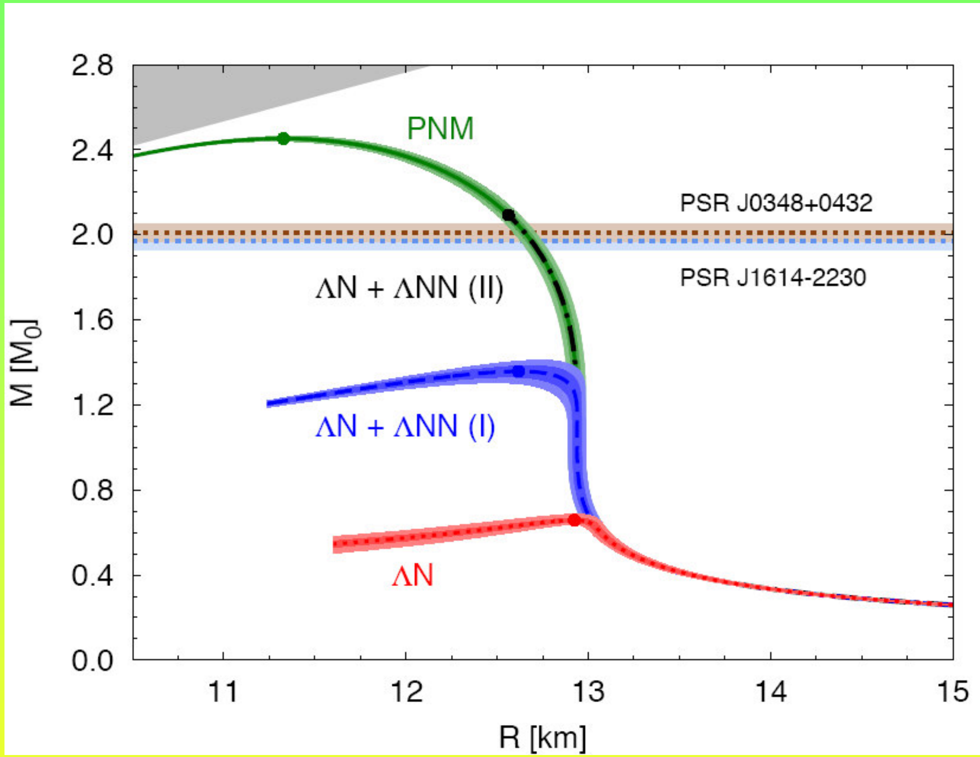
Two-meson exchange NNY potential

D. Logoteta, I. Vidaña, C. Providencia, Nucl. Phys. A 914 (2013) 433

Microscopic EOS for hyperonic matter: AFDM

Gandolfi's talk this morning, Lonardoni's talk in this section





(n , Λ) - matter

Av8' + UXI + ΛNN

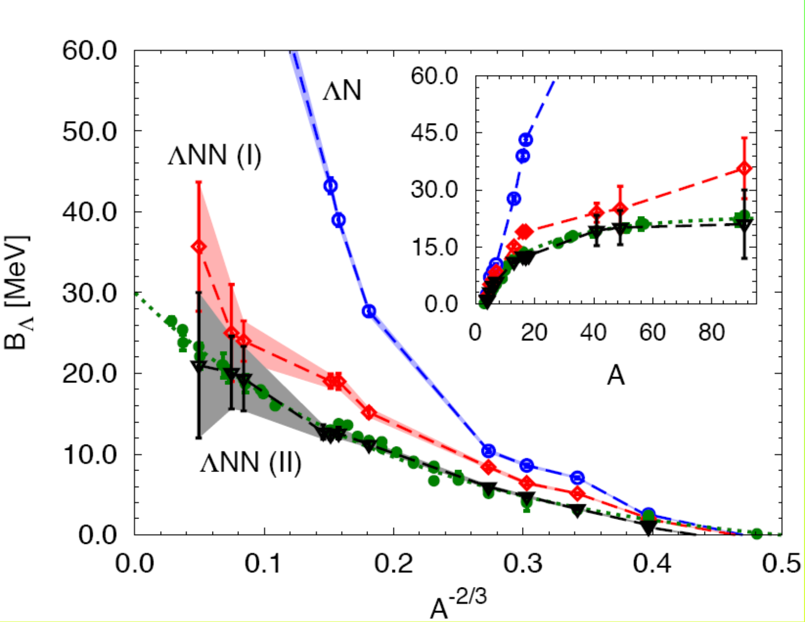
D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva, Phys. Rev. Lett. 114 (2015) 092301

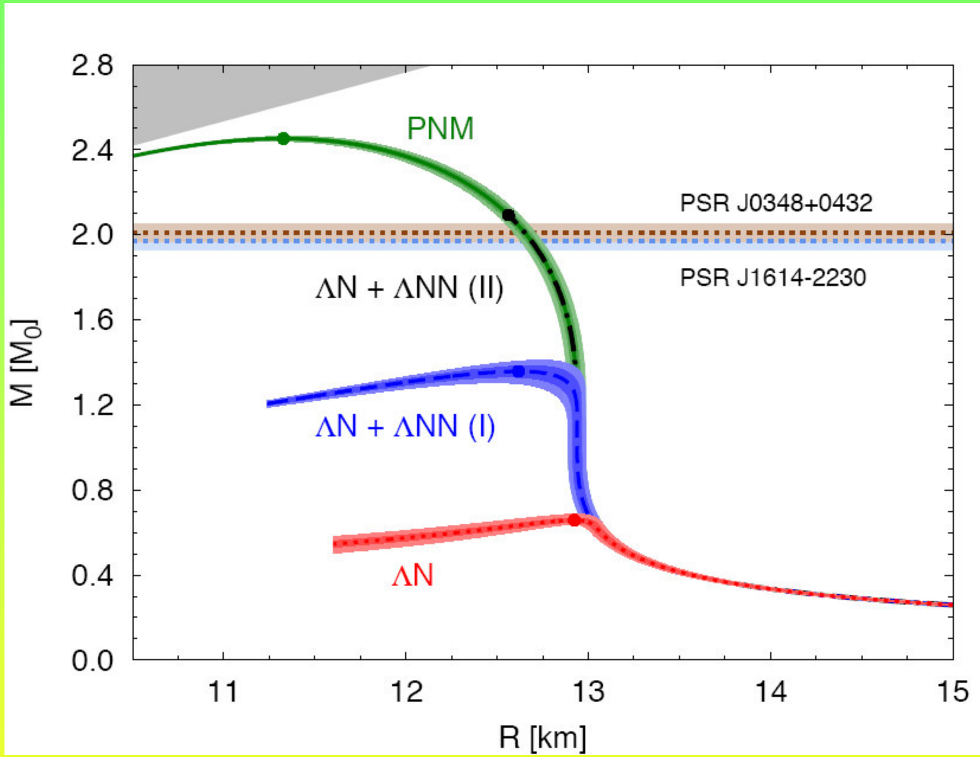
Repulsive ΛNN
(Bodmer, Usmani, Carlson, 1984)
Parameters fixed to fit
B_Λ **Λ hyeprnuclei (A ≤ 91)**

Hypernuclei can not constrain YNN interactions at high desity

Microscopic EOS for hyperonic matter: AFDM

Gandolfi's talk this morning, Lonardoni's talk in this section





(n , Λ) - matter

Av8' + UXI + ΛNN

D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva, Phys. Rev. Lett. 114 (2015) 092301

Repulsive ΛNN
(Bodmer, Usmani, Carlson, 1984)
Parameters fixed to fit
B_Λ **Λ hyeprnuclei (A ≤ 91)**

Within this model

"Hyperon Stars" do not contain hyperons

Relativistic Mean Field models for the hyperonic matter EOS

- **Strong vector-meson mediated repulsive interaction**

- ○ increase of $g_{\rho Y}$ coupling ("σωρ" model)
- ○ inclusion of vector mesons with hidden strangeness (ϕ meson)

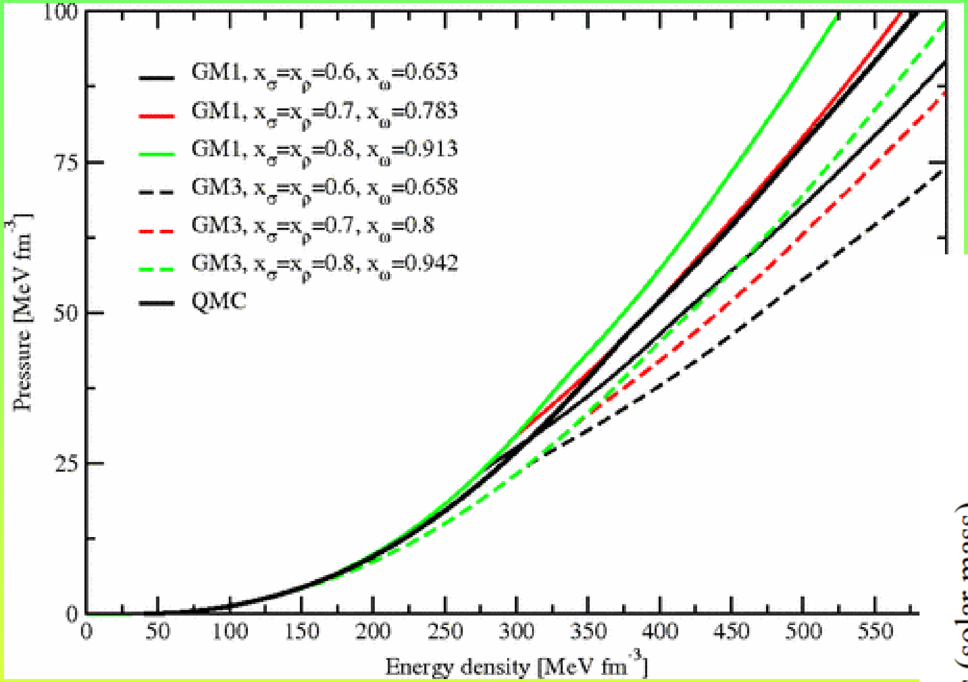
- **density dependent coupling constants**

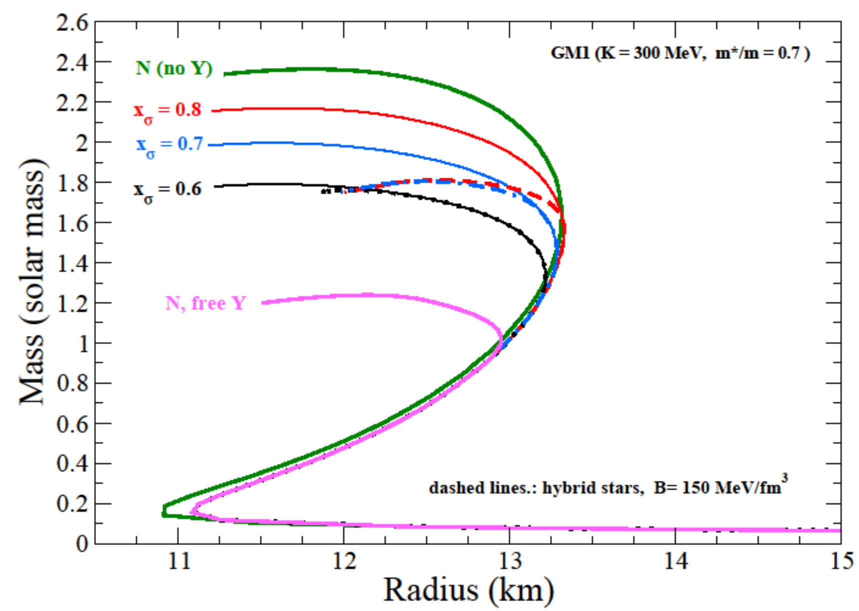
Miyatsu's talk in this section

H. Huber, M.K. Weigel, F. Weber, Z. Naturforsch. 54A (1999) 77
F. Hoffman, C.M. Kleil, H. Lenske, Phys. Rev. C 64 ((2001) 034314
V. Dexheimer, S. Schramm, Astrophys. J. 683 (2008) 943
I. Bombaci, P.K. Pandha, C. Providencia, I. Vidana, Phys. Rev. D 77 (2008) 083002
A. Taurines, C.Vasconcellos, M. Malheiro, M. Chiapparini, Mod. Phys. Lett. A 15 (2000) 1789
T. Miyatsu, T. Katayama, K. Saito, Phys. Lett. B 709 (2012) 242
S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Phys. Rev. C 85 (2012) 065802
E.N.E. van Dalen, G. Colucci, A. Sedrakian, Phys. Lett. B 734 (2014) 383

Glendenning – Moszkowski EOS

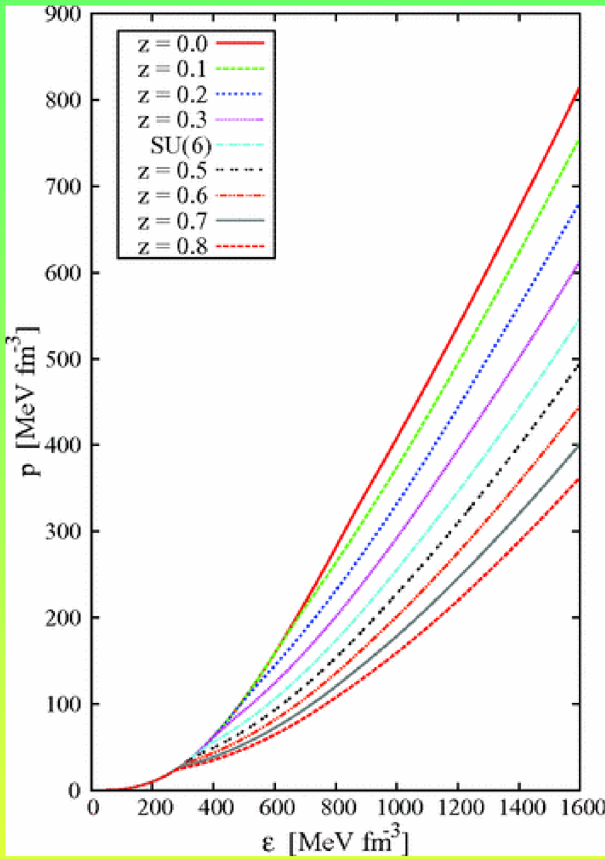
$$g_{\sigma Y} = x_\sigma g_{\sigma N}$$
$$g_{\omega Y} = x_\omega g_{\omega N}$$
$$g_{\rho Y} = x_\rho g_{\rho N}$$
$$x_\rho = x_\sigma$$

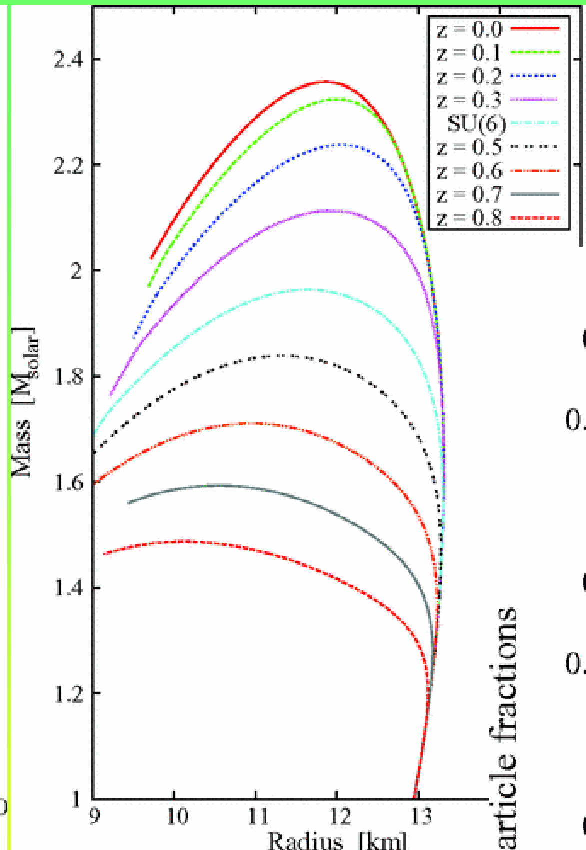


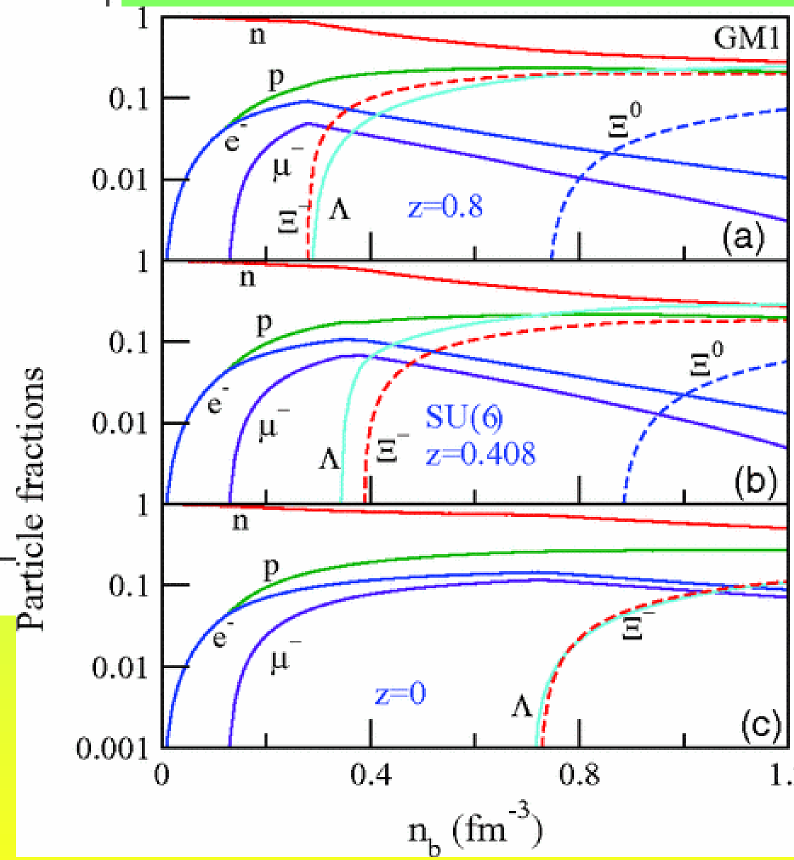


I. Bombaci, P.K. Pandha, C. Providencia, I. Vidana,
Phys. Rev. D 77 (2008) 083002

increasing $g_{\rho Y}$ and $g_{\omega Y}$ → **M_{max} increases and the stellar hyperon content decreases**







S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Phys. Rev. C 85 (2012) 065802

Neutron Stars in the QCD phase diagram

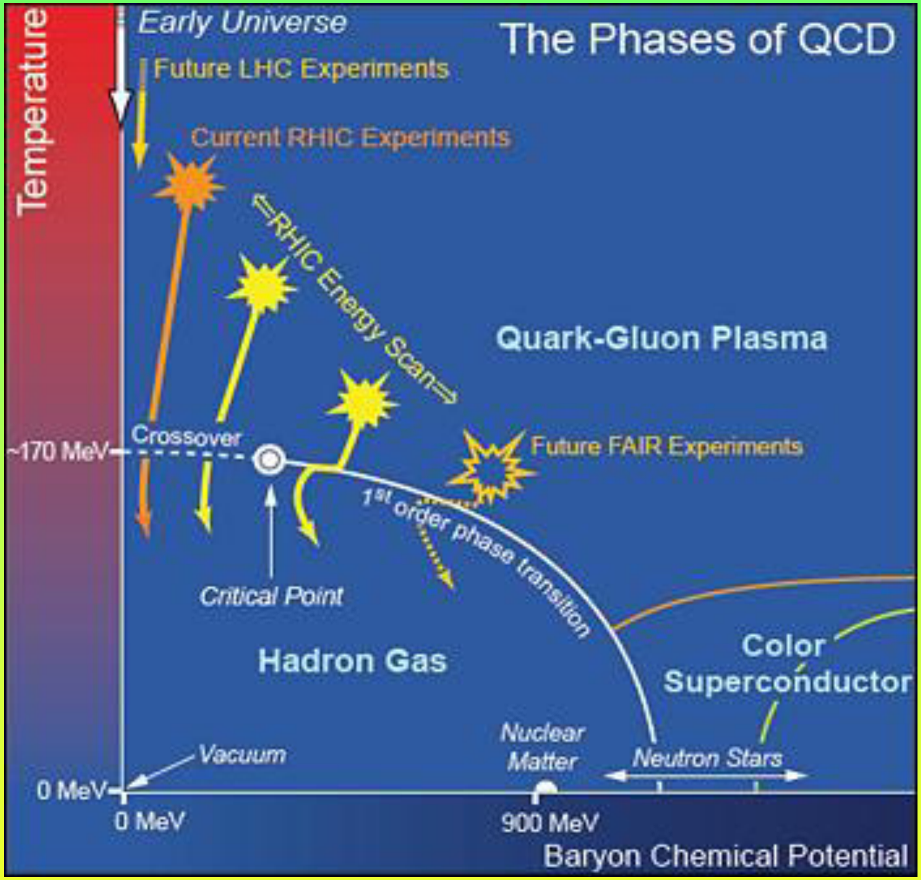
Lattice QCD
at μ_b=0 and finite T

- ► **The transition to Quark Gluon Plasma is a crossover**
  Aoki et ,al., Nature, 443 (2006) 675

- ► **Deconfinement transition temperature T_c**

HotQCD Collaboration
T_c= 154 ± 9 MeV
Bazarov et al., Phys.Rev. D85 (2012) 054503

Wuppertal-Budapest Collab.
T_c= 147 ± 5 MeV
Borsanyi et al., J.H.E.P. 09 (2010) 073

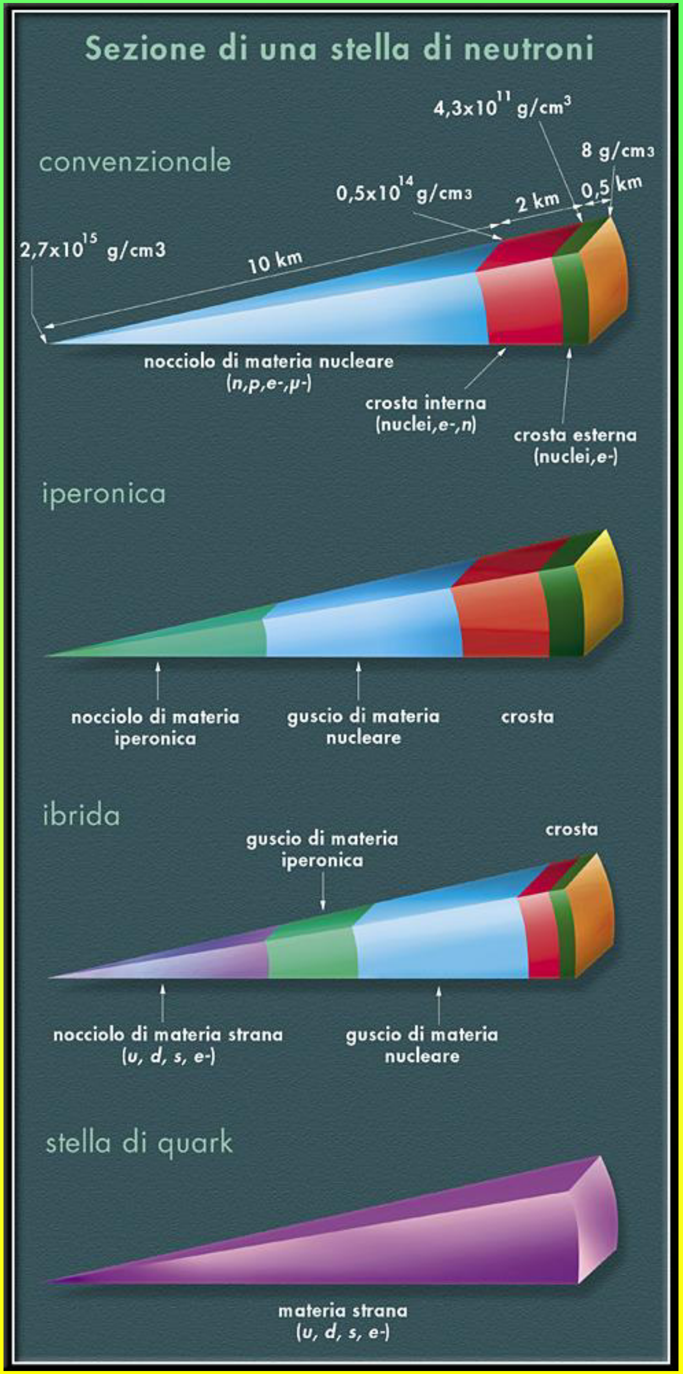


Neutron Stars: high μ_b and low T

Lattice QCD calculations are presently not possible
Quark deconfinement transition expected of the first order
Z. Fodor, S.D. Katz, Prog. Theor Suppl. 153 (2004) 86

"A link between lattice QCD and measured neutron star masses"
I. Bombaci, D. Logoteta, Mont. Not. Royal Astron. Soc. 433 (2013) L79

“Neutron Stars”

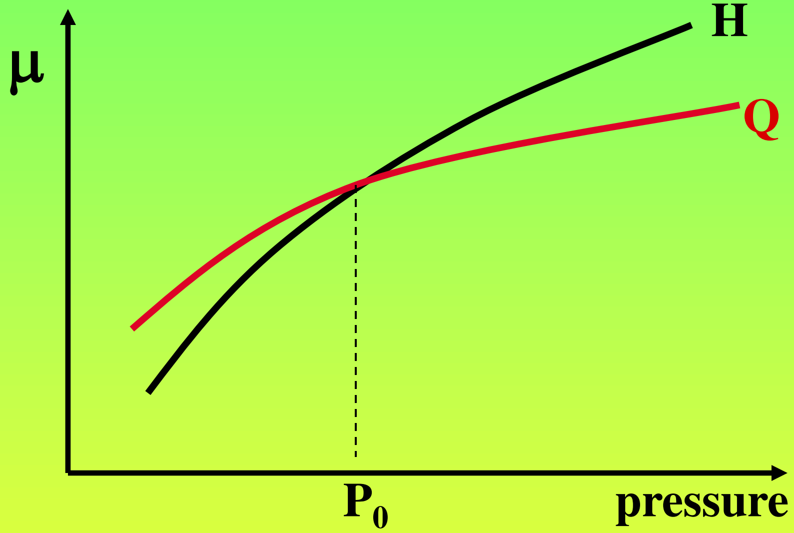


I. Bombaci, A. Drago, INFN Notizie, n. 13, 15 (2003)

Nucleon Stars
Hyperon Stars
} **Hadronic Stars**

Hybrid Stars
Strange Stars
} **Quark Stars**

1st order phase transitions are triggered by the **nucleation** of a **critical size drop** of the **new (stable) phase** in a **metastable mother phase**



Virtual drops of the stable phase are created by small localized **fluctuations** in the state variables of the **metastable phase**

Gibbs' criterion for phase equilibrium

$$\mu_H = \mu_Q \equiv \mu_0$$

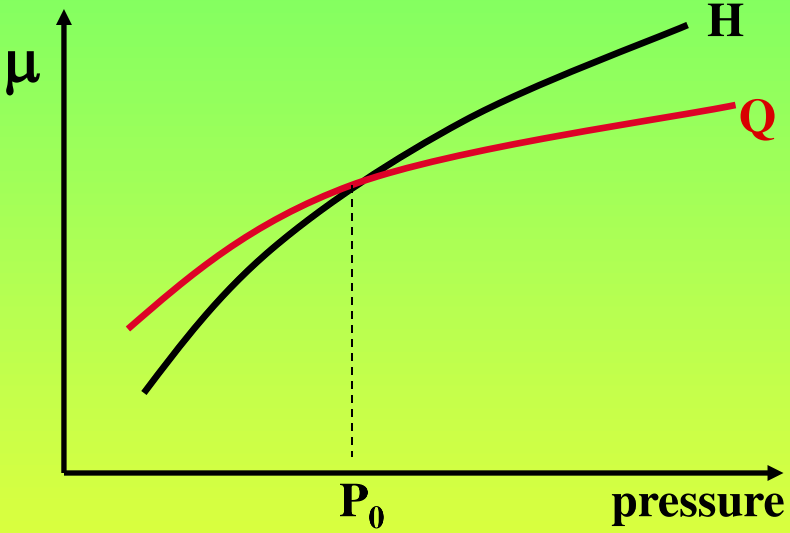
$$T_H = T_Q \equiv T$$

$$P(\mu_H) = P(\mu_Q) \equiv P(\mu_0) \equiv P_0$$

$$\mu_H = \frac{\varepsilon_H + P_H - s_H T}{n_{b,H}}$$

$$\mu_Q = \frac{\varepsilon_Q + P_Q - s_Q T}{n_{b,Q}}$$

1st order phase transitions are triggered by the **nucleation** of a **critical size drop** of the **new (stable) phase** in a **metastable mother phase**

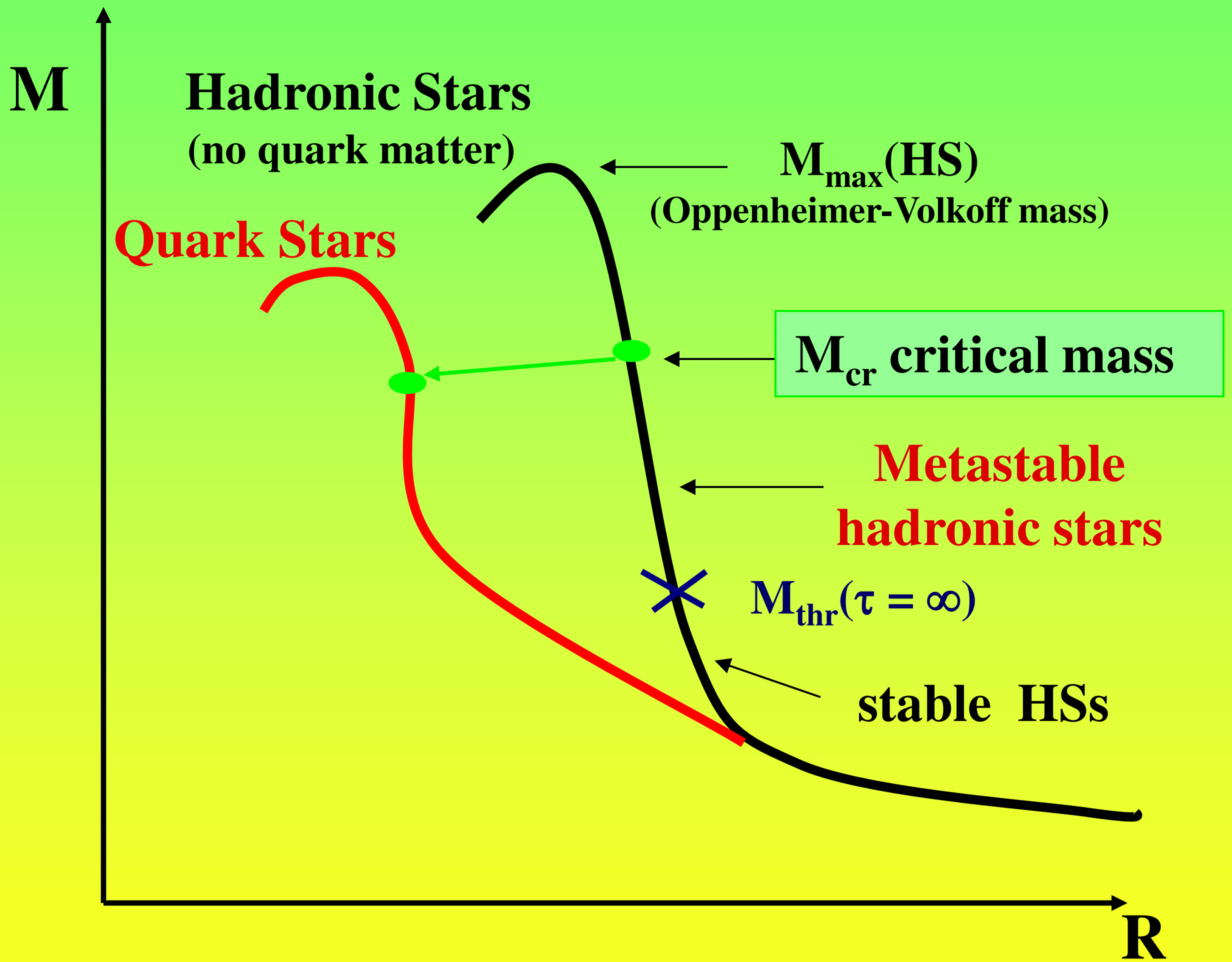


Virtual drops of the stable phase are created by small localized **fluctuations** in the state variables of the **metastable phase**

Astrophysical consequences of the **nucleation process of quark matter (QM)** in the **core of massive pure hadronic compact stars (“Hadronic Stars”, HS).**

Berezhiani, Bombaci, Drago, Frontera, Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, G. Lugones, I. Vidaña, Astron. &Astrophys. 462 (2007) 1017

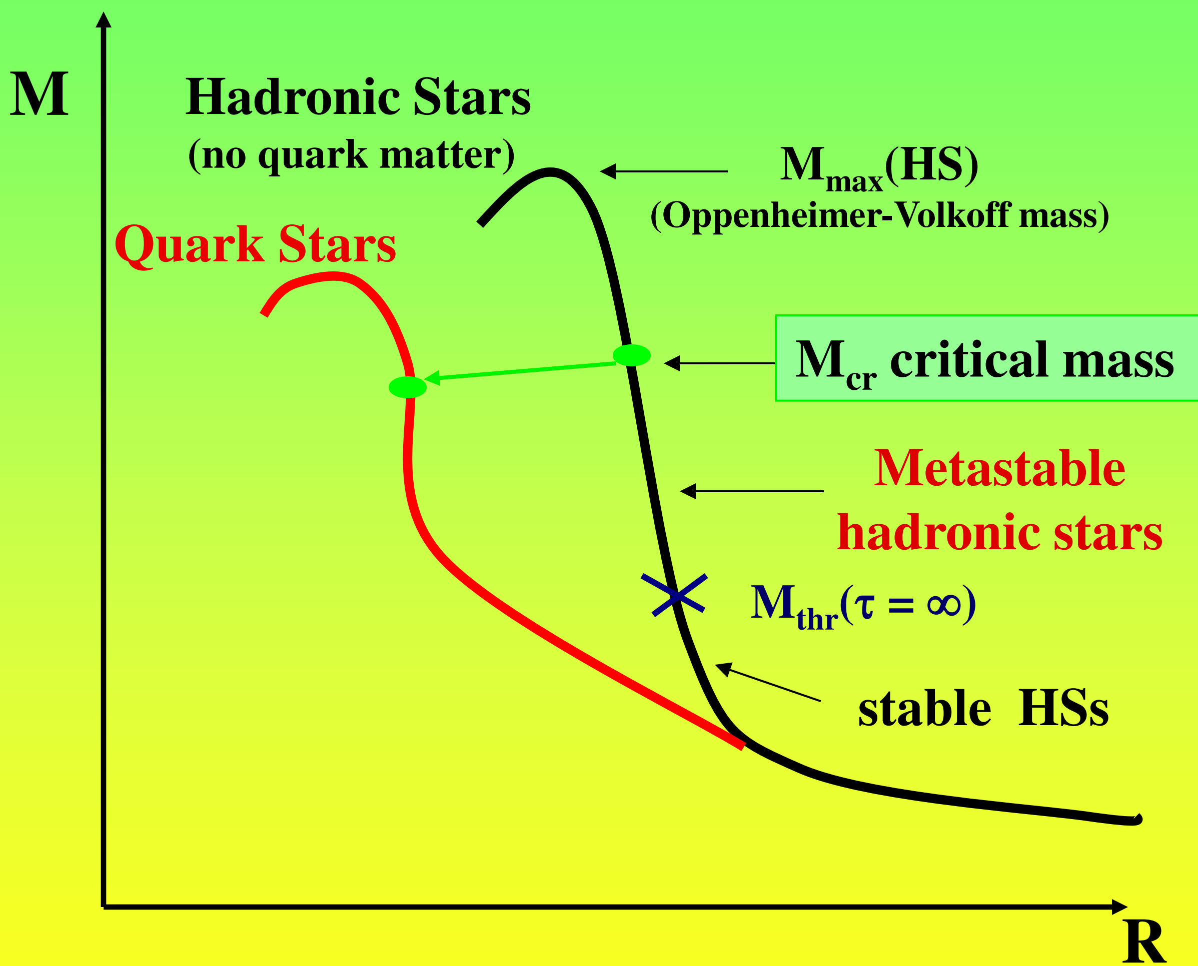
Metastability of Hadronic Stars



Hadronic Stars above a threshold value of their gravitational mass are **metastable** to the **conversion** to **Quark Stars (QS)** (hybrid stars or strange stars)

Berezhiani, Bombaci, Drago, Frontera, Lavagno, Astrophys. Jour. 586 (2003) 1250
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, G. Lugones, I. Vidaña, Astron. &Astrophys. 462 (2007) 1017

Metastability of Hadronic Stars



Berezhiani, Bombaci, Drago, Frontera, Lavagno, Astr
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 61
I. Bombaci, G. Lugones, I. Vidaña, Astron. &Astroph

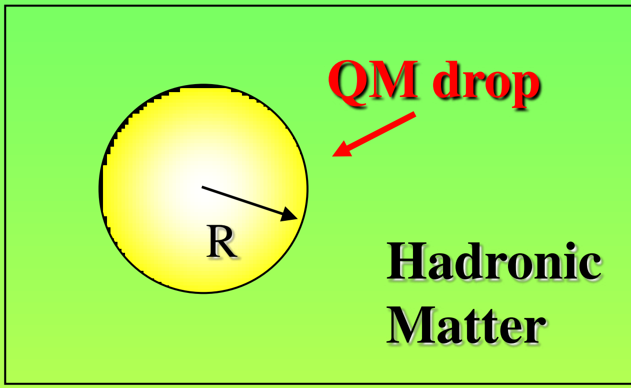
- M_{cr} , critical mass of hadronic stars.
- Two branches of compact stars
- stellar conversion HS→QS

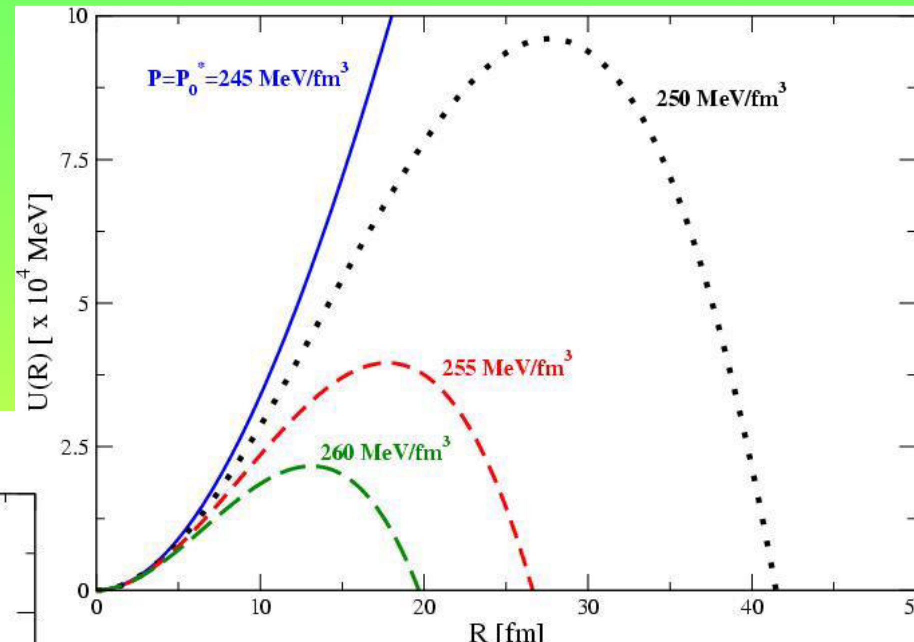
$E_{conv} \sim 10^{53}$ erg (possible energy source for some GRBs)

extension of the concept of limiting mass of compact stars with respect to the *classical* one given by Oppenheimer and Volkoff

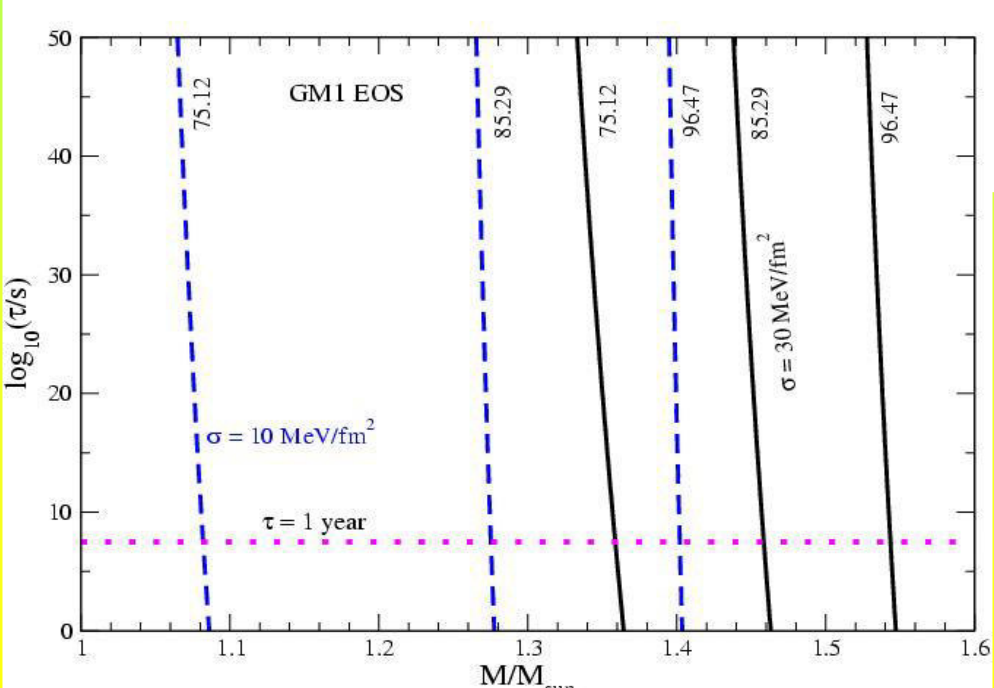
Quantum nucleation theory

I.M. Lifshitz and Y. Kagan, 1972; K. Iida and K. Sato, 1998





Hadronic Star mean-life time



$$U(R) = (4/3)\pi R^3 n_{Q*} (\mu_{Q*} - \mu_H) + 4\pi\sigma R^2$$

I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314

The critical mass of metastable Hadronic Stars

Def.: $M_{cr} \equiv M_{HS}(\tau = 1\ yr)$

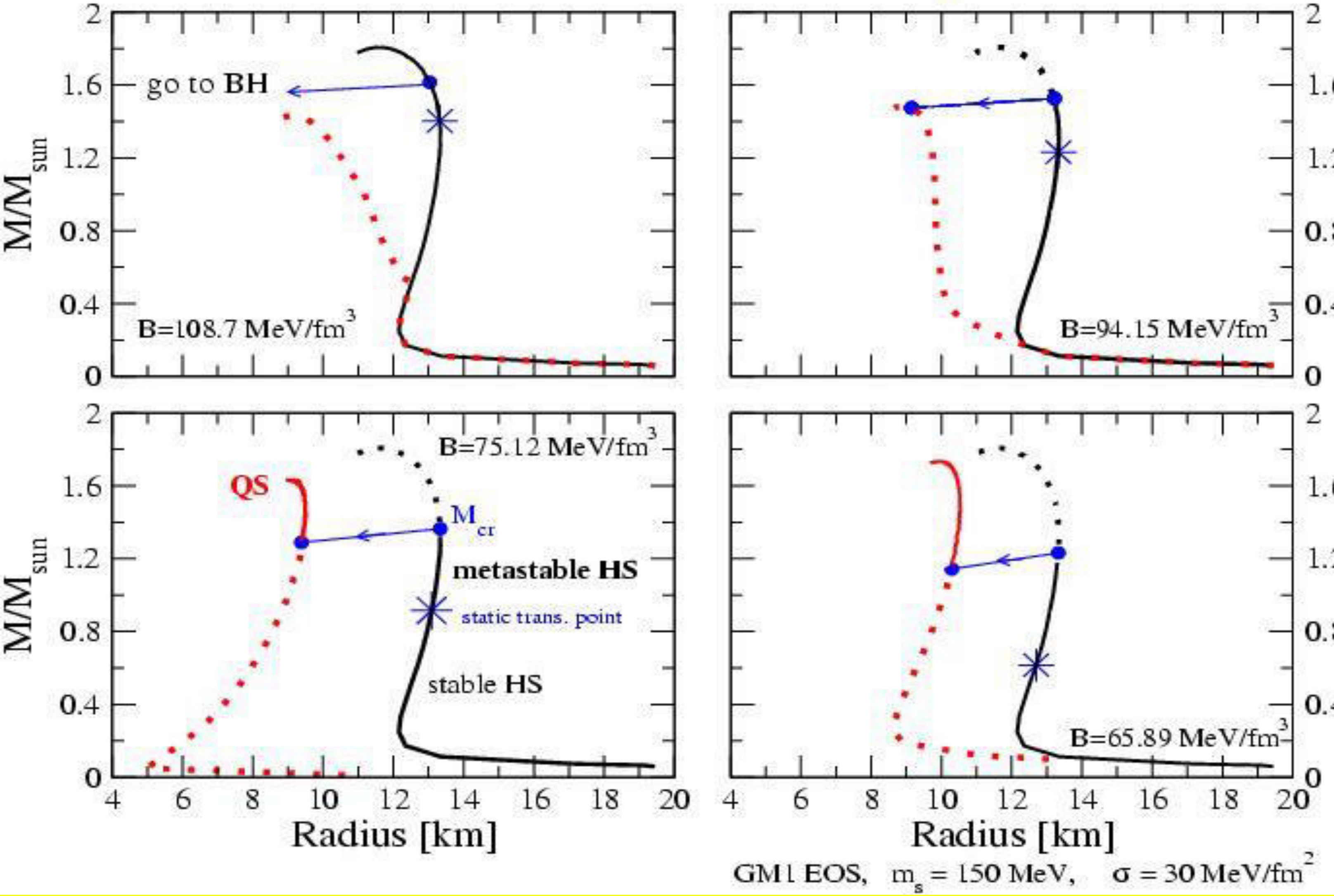
- **HS with $M_{thr} < M_{HS} < M_{cr}$ are metastable with $\tau = 1\ yr \div \infty$**

- **HS with $M_{HS} > M_{cr}$ are very unlikely to be observed**

↓

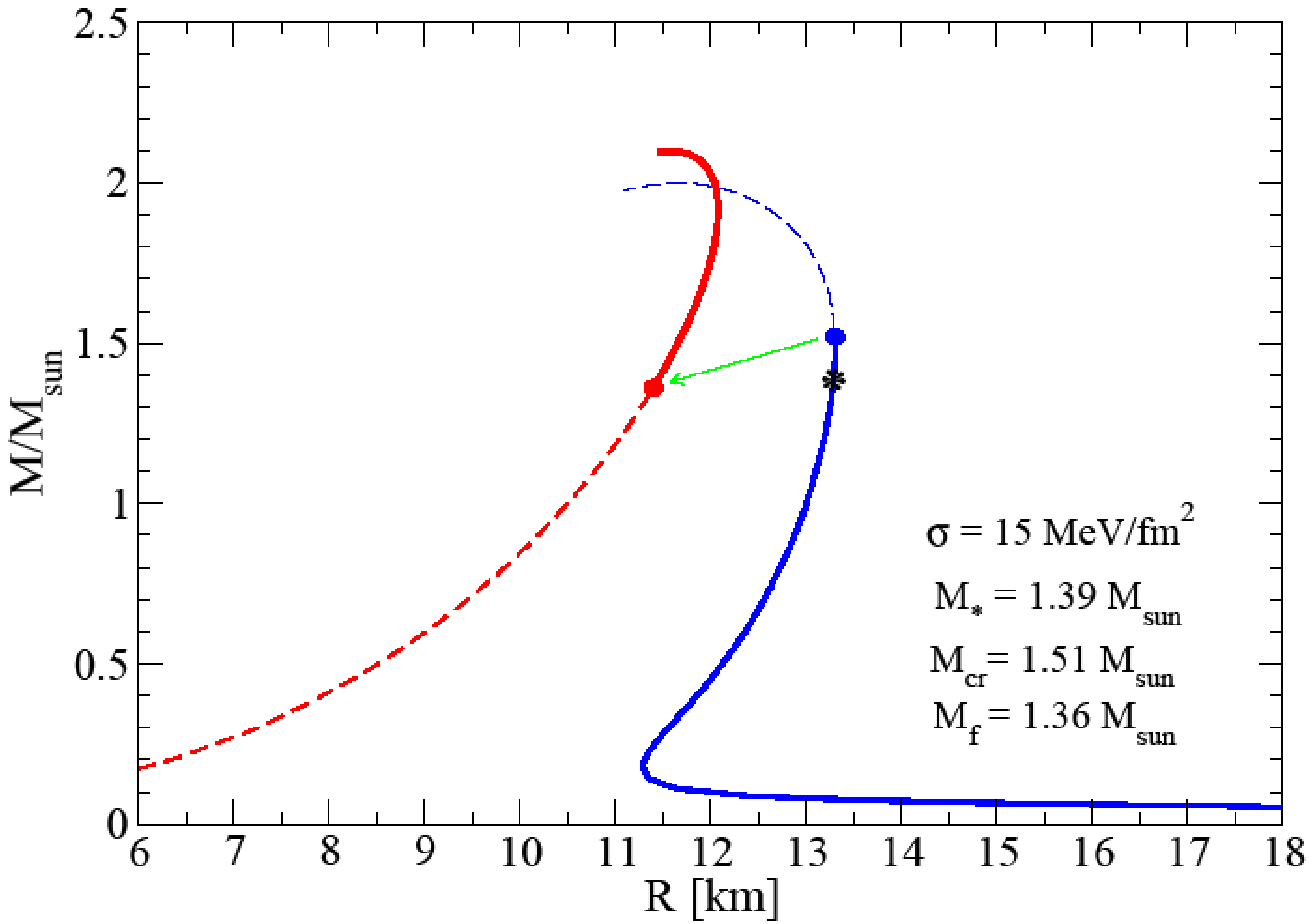
The critical mass M_{cr} plays the role of an effective maximum mass for the hadronic branch of compact stars

The two families of Compact Stars



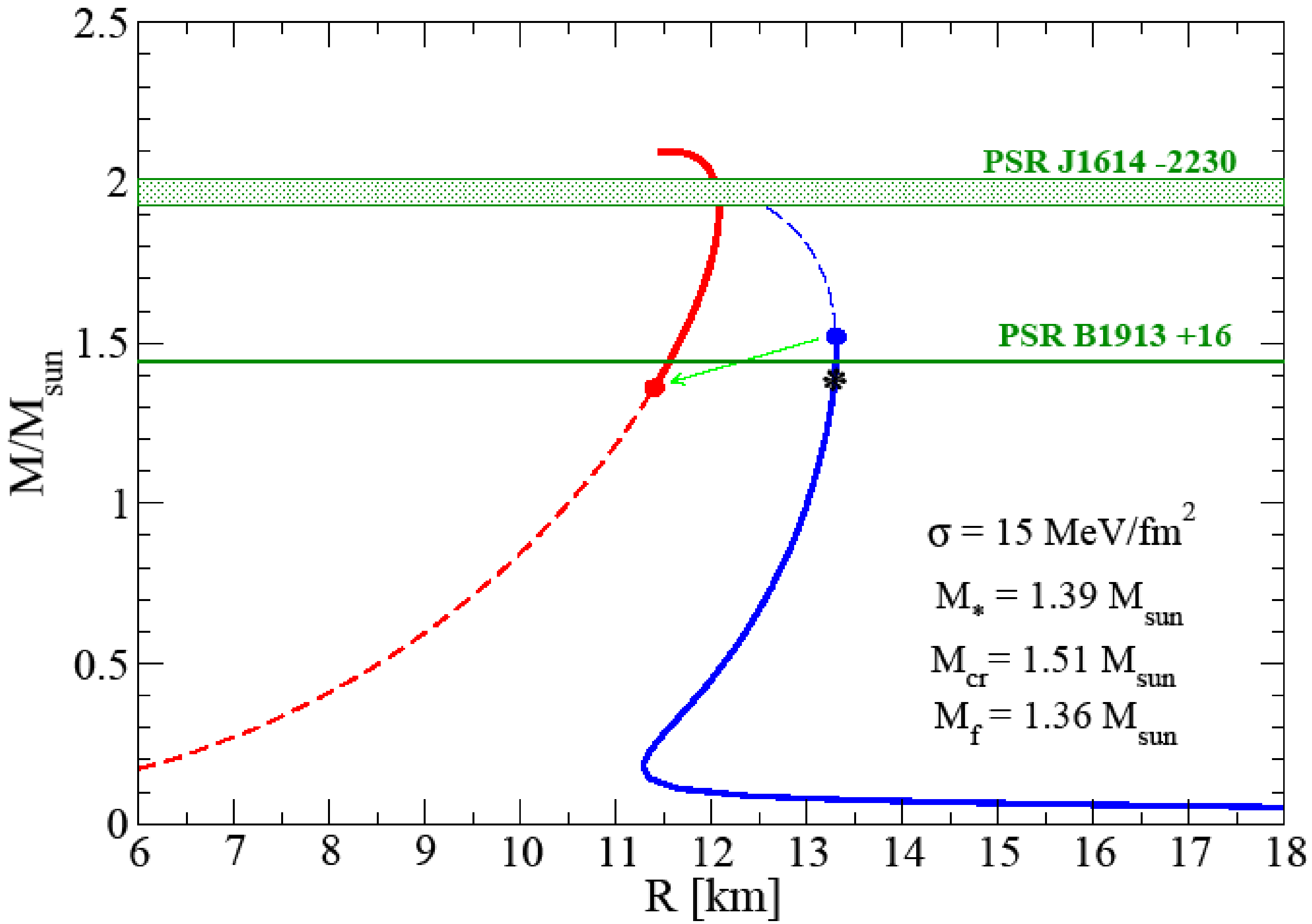
Hadronic Stars: nucleons + hyperons

Bombaci, Parenti, Vidaña, Astrophys. Jour. 614 (2004) 314



I. Bombaci, D. Logoteta (2014)

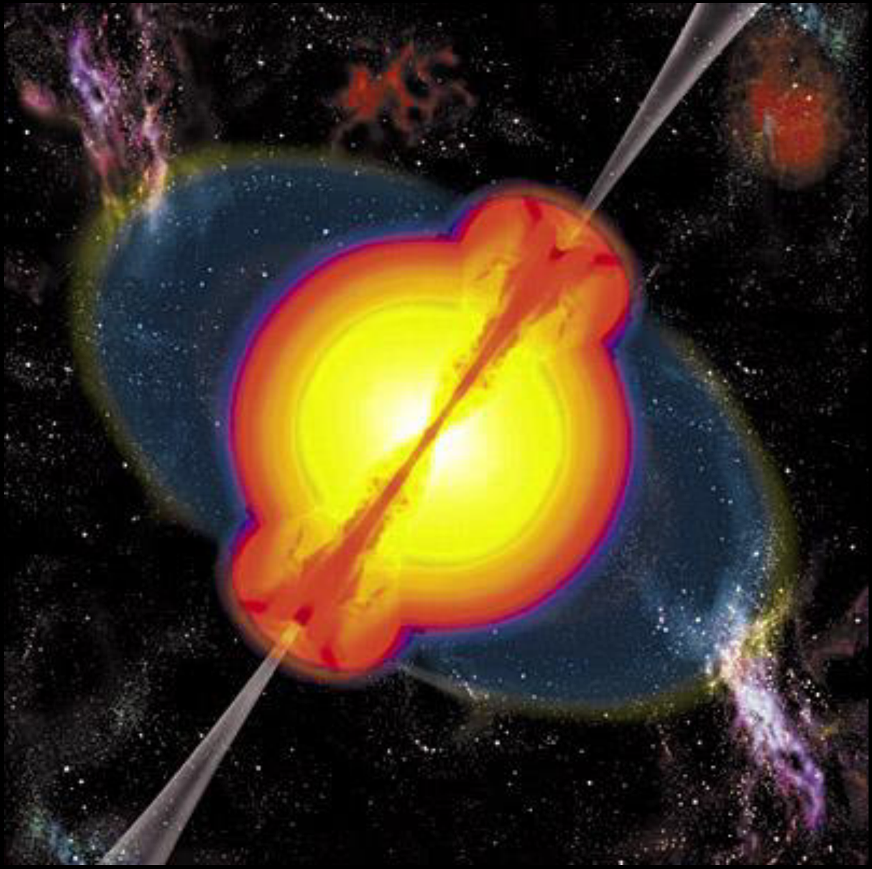
SQM EOS: Alford et al. Astrophys. J. 629 (2005); Fraga et al., Phys. Rev. D 63 (2001)



I. Bombaci, D. Logoteta (2014)

SQM EOS: Alford et al. Astrophys. J. 629 (2005); Fraga et al., Phys. Rev. D 63 (2001)

Total energy released in the stellar conversion



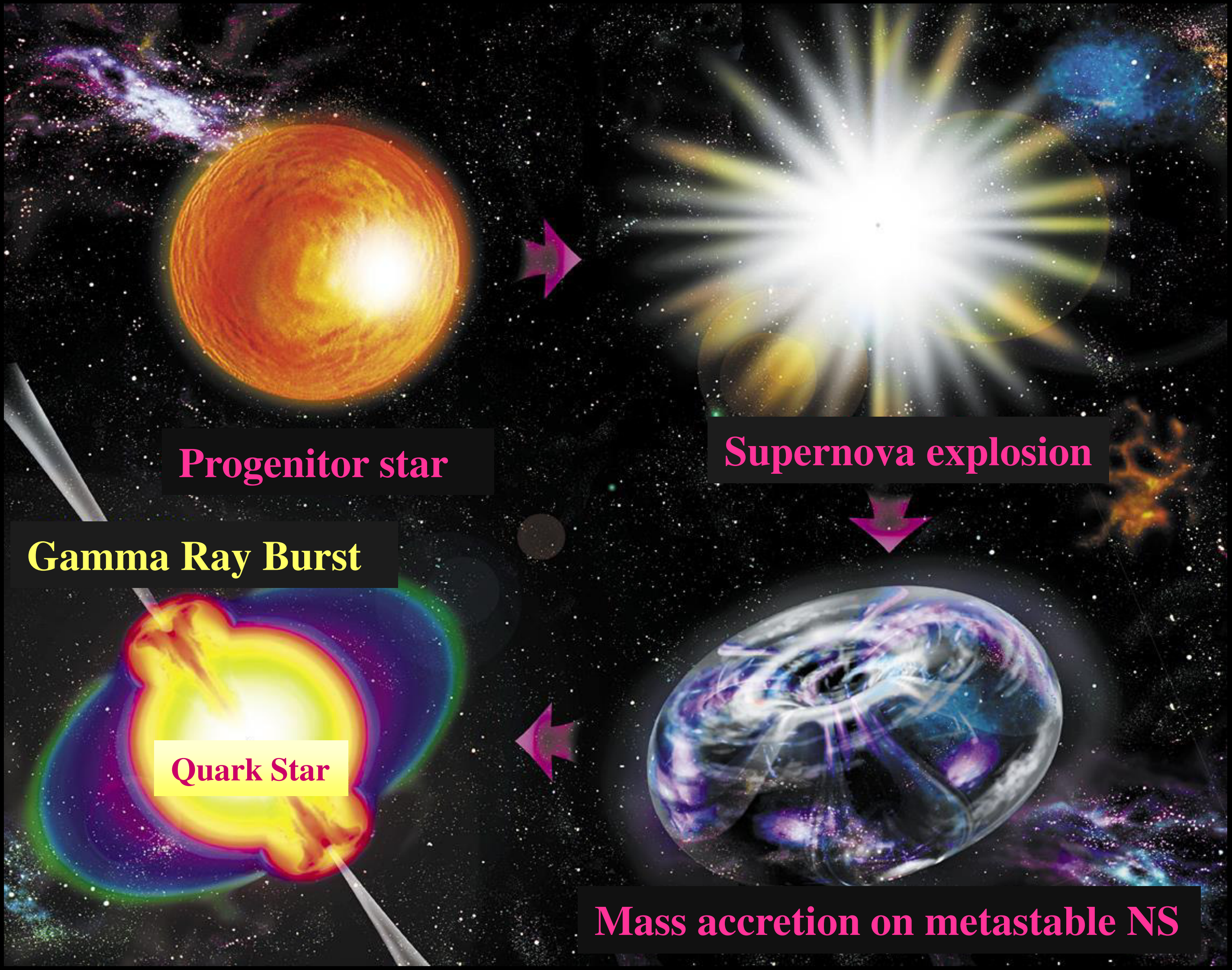
Assuming that the **stellar baryonic mass is conserved** during the stellar conversion, the total energy released in the process is :

$$E_{conv} = M_{cr} - M_{QS}(M^{b}_{cr})$$

$$\sim 10^{53}\ \mathrm{erg}$$

I. Bombaci, & B. Datta, Astrophys. J. Lett. 530 (2000) L69

Supernova-GRB connection: Hadronic Star → Quark Star conversion model



Berezhiani, Bombaci, Drago, Frontera, Lavagno, Astrophys. Jour. 586 (2003) 1250

Summary

"Hyperon puzzle" in Neutron star physics $M_{max} < 2\, M_{\odot}$ ⟹

⟹ **quest for extra pressure at high densities**

(i)

- ► **strong short-range repulsion in NY, YY interactions**
- ► **repulsive NNY, NYY, YYY 3-baryon interactions**
- ► **strong vector-meson mediated repulsive interaction (RMF)**

$$\frac{|S|}{N_B} \approx 0$$

(ii) or, the transition to Strange Quark Matter produce a stiffening of the EOS due e.g. to perturbative quark interactions

NS → Quark Stars (hybrid or strange stars)

$$\frac{|S|}{N_B} \approx 1$$