

**XIV Workshop on
Lepton-Nucleus Scattering**
Marciana Marina, Isola d'Elba
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The hyperon puzzle in Neutron Stars

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INFN Sezione di Pisa**



Neutron Stars: bulk properties

Mass	$M \sim 1.5 M_{\odot}$
Radius	$R \sim 10 \text{ km}$
Centr. Density	$\rho_c = (4 - 8) \rho_0$
Compactness	$R/R_g \sim 2 - 4$
Baryon number	$A \sim 10^{57}$
Binding energy	$B \sim 10^{53} \text{ erg}$
$B/A \sim 100 \text{ MeV}$	$B/(Mc^2) \sim 10\%$

Stellar structure:
General Relativity

Giant “atomic nucleus”
or “hypernucleus”
bound by **gravity**

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

$$R_{g \odot} = 2.95 \text{ km}$$

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

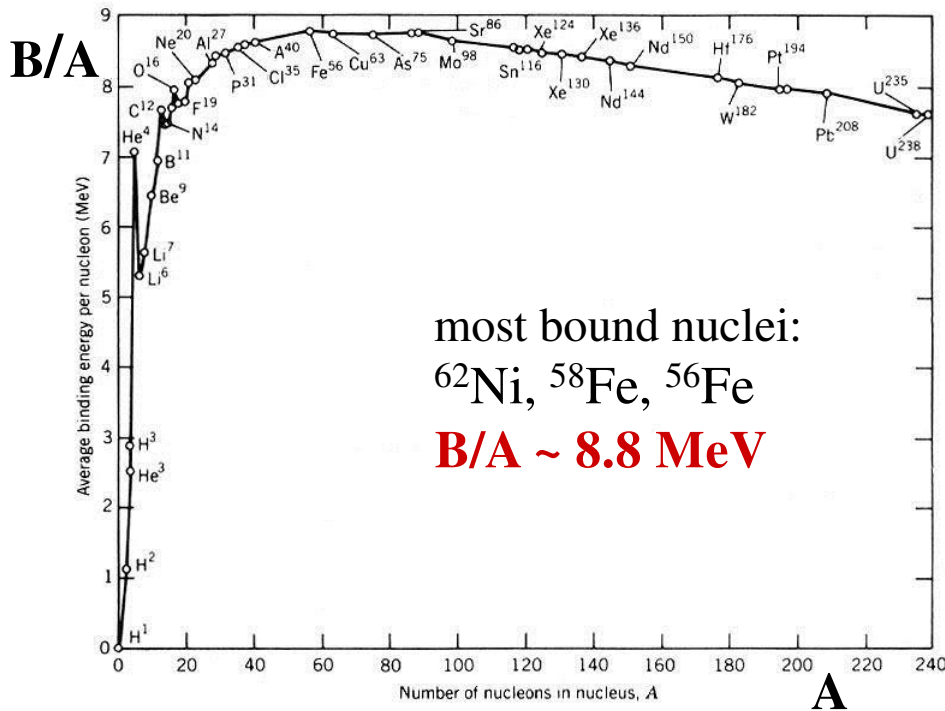
$$R_g \equiv 2GM/c^2 \text{ (Schwarzschild radius)}$$

Atomic Nuclei: bulk properties

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

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

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



$B/(Mc^2)$
 $\sim (0.1-1)\%$

bound by
nuclear
interactions

Relativistic equations for stellar structure

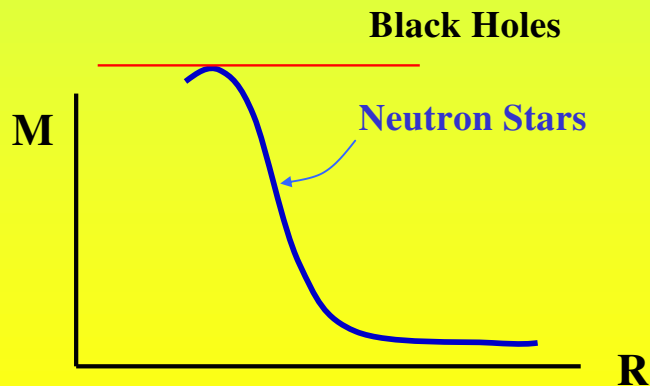
Tolman – Oppenheimer – Volkov equations (TOV)

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

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

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

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



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

Two “heavy” Neutron Stars

PSR J1614–2230

$$M_{\text{NS}} = 1.97 \pm 0.04 M_{\odot}$$

NS – WD binary system (He WD)

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

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

$i = 89.17^{\circ} \pm 0.02^{\circ}$ (inclination angle)

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

PSR J0348+0432

$$M_{\text{NS}} = 2.01 \pm 0.04 M_{\odot}$$

NS – WD binary system

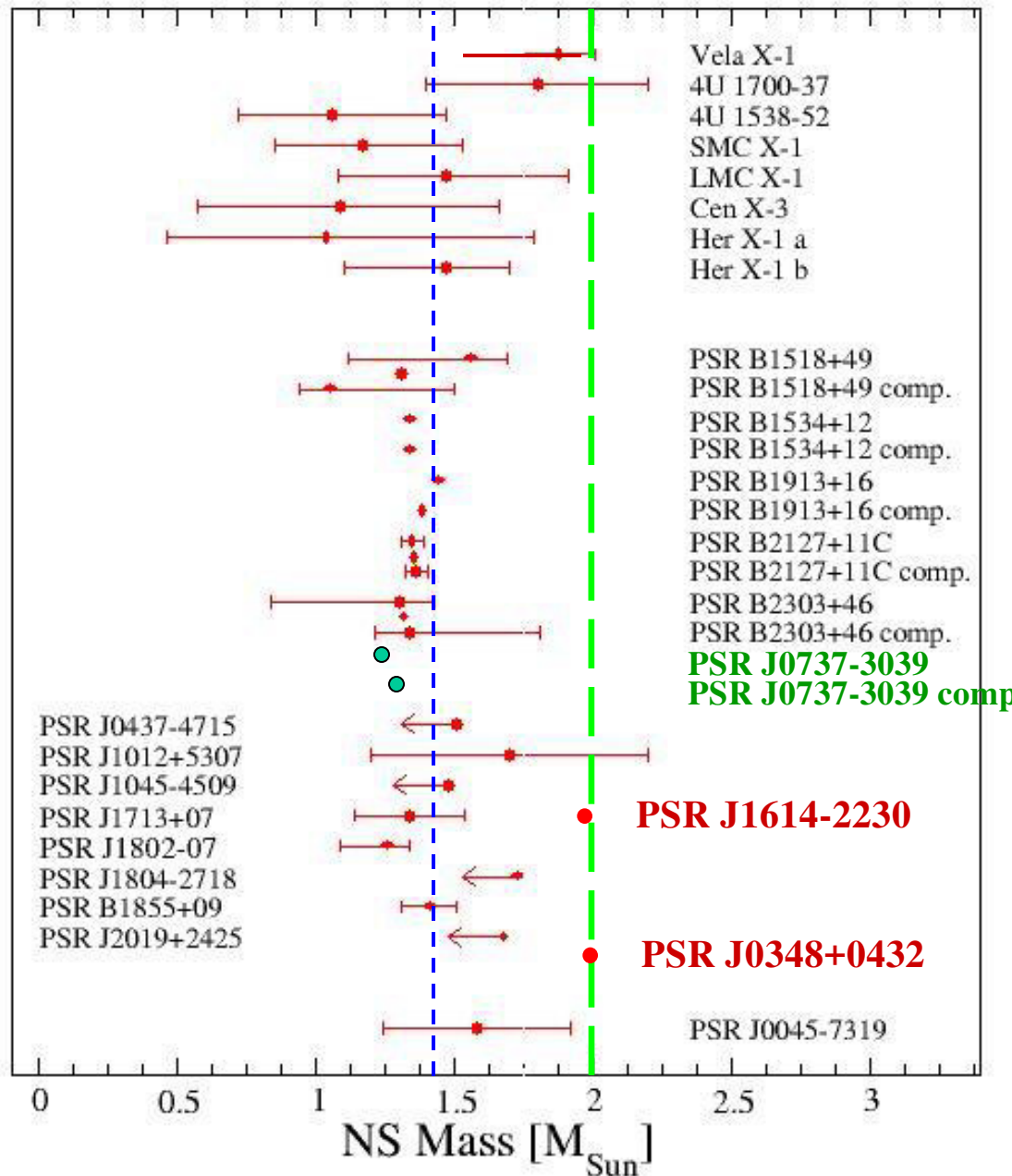
$M_{\text{WD}} = 0.172 \pm 0.003 M_{\odot}$ (companion mass)

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

$i = 40.2^{\circ} \pm 0.6^{\circ}$ (inclination angle)

Antoniadis et al., Science 340 (2013) 448

Measured Neutron Star Masses



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



**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 principle**

Stellar constituents are different species of **identical fermions** (n, p, ..., e^- , μ^-)
→ antisymmetric wave function for particle exchange → Pauli principle

Chemical potentials $\mu_n, \mu_p, \dots, \mu_e$ 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

β -stable nuclear matter

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

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

$$\mu_e \geq m_\mu$$

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

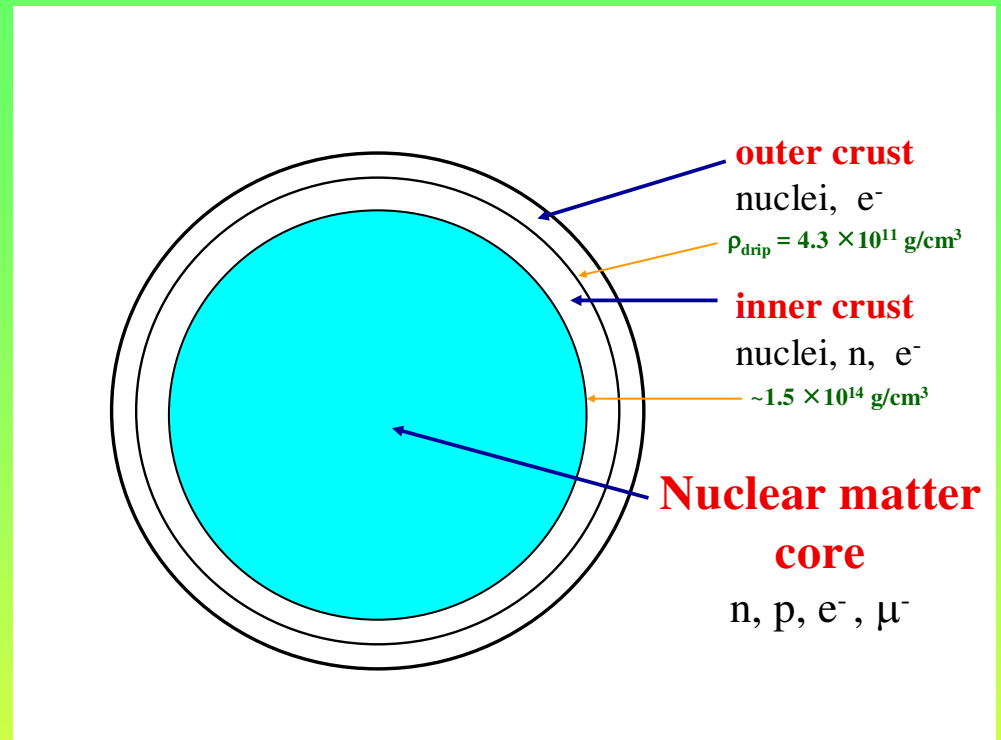
Equilibrium with respect to the weak interaction processes

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

$$\mu_\mu = \mu_e$$

Charge neutrality

$$n_p = n_e + n_\mu$$



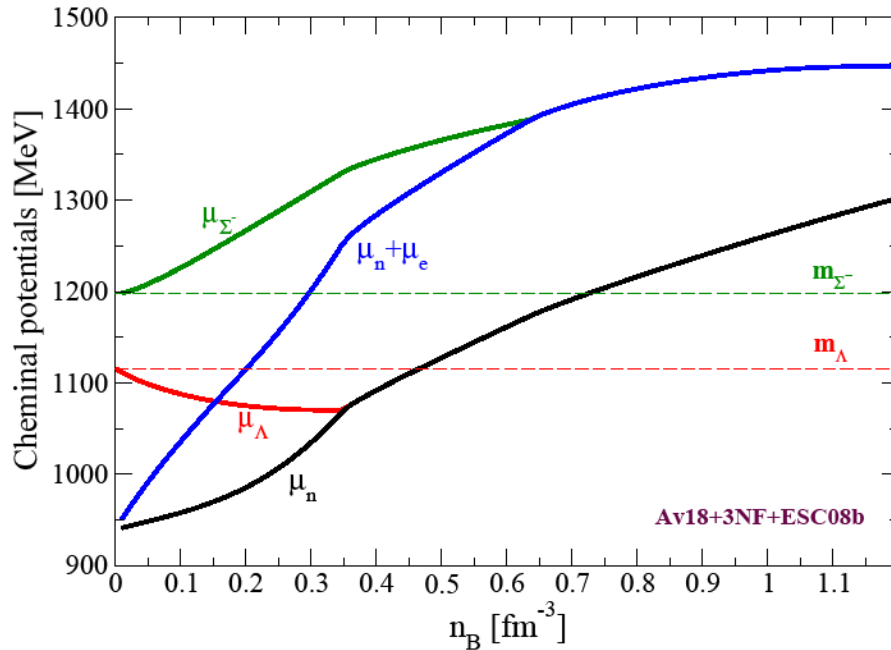
neutrino-free matter

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

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

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

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



D. Logoteta, I. Bombaci (2014)

Hyperons appear in the stellar core above a threshold density

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

$$\mu_p = \mu_n - \mu_e = \mu_{\Sigma^+}$$

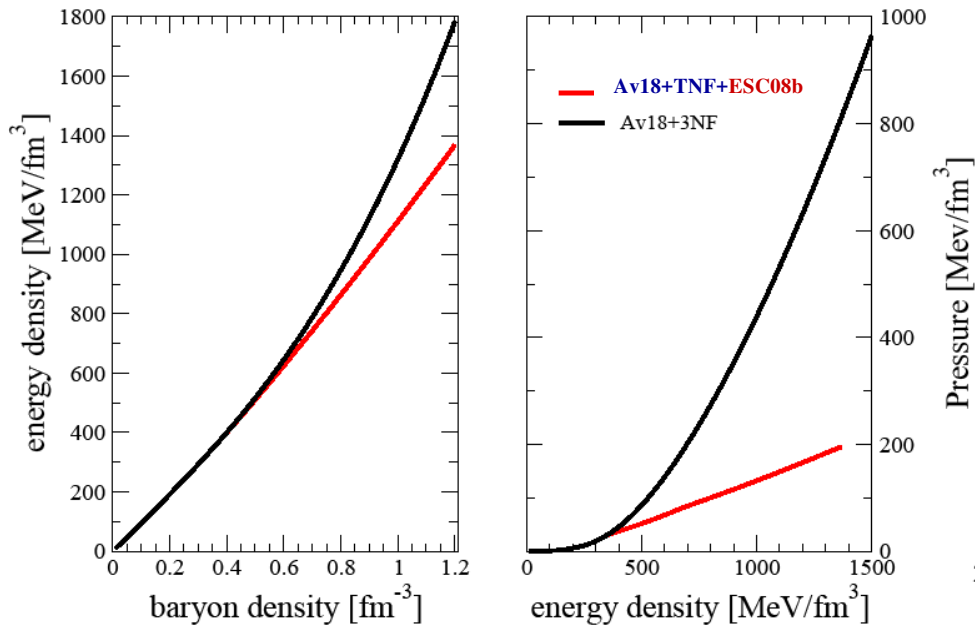
$$\mu_n = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_{\Lambda}$$

$$\mu_n + \mu_e = \mu_{\Sigma^-} = \mu_{\Xi^-}$$

$$\mu_{\mu} = \mu_e$$

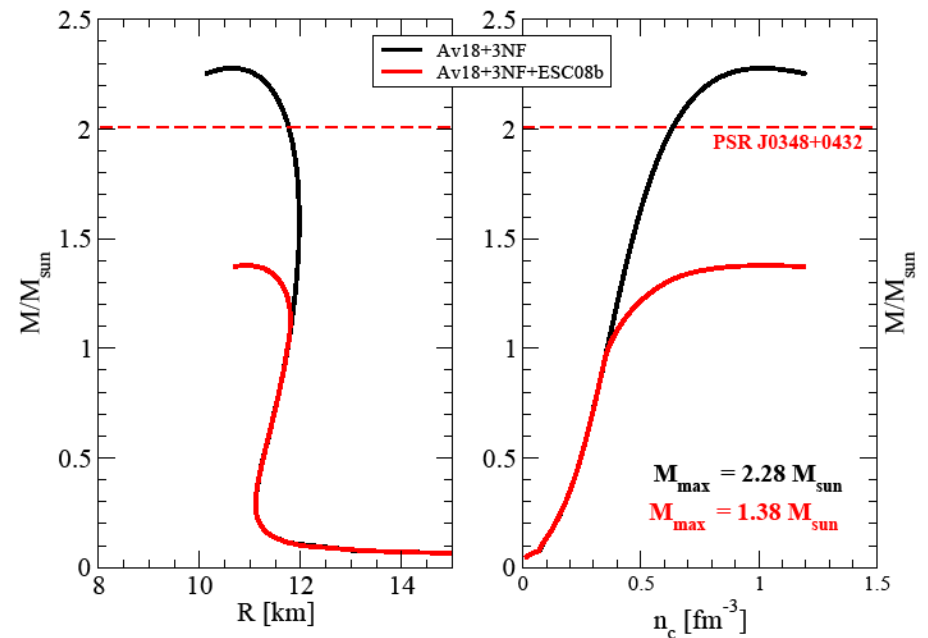
$$n_p + n_{\Sigma^+} = n_e + n_{\mu} + n_{\Sigma^-} + n_{\Xi^-}$$

Equation of State of Hyperonic Matter



**hyperons produce a
strong softening
of the EOS**

Stellar mass



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

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

not compatible with measured NS masses

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

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 scattering data with $\chi^2/\text{datum} \sim 1$

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: $n_0 = 0.16 \text{ fm}^{-3}$, $E/A = -16 \text{ MeV}$

	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 $n = 0.16 \text{ fm}^{-3}$

$$E^{\text{pot}}(2\text{BF})/A \sim -40 \text{ MeV}$$

$$E^{\text{pot}}(3\text{BF})/A \sim -1 \text{ MeV}$$

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

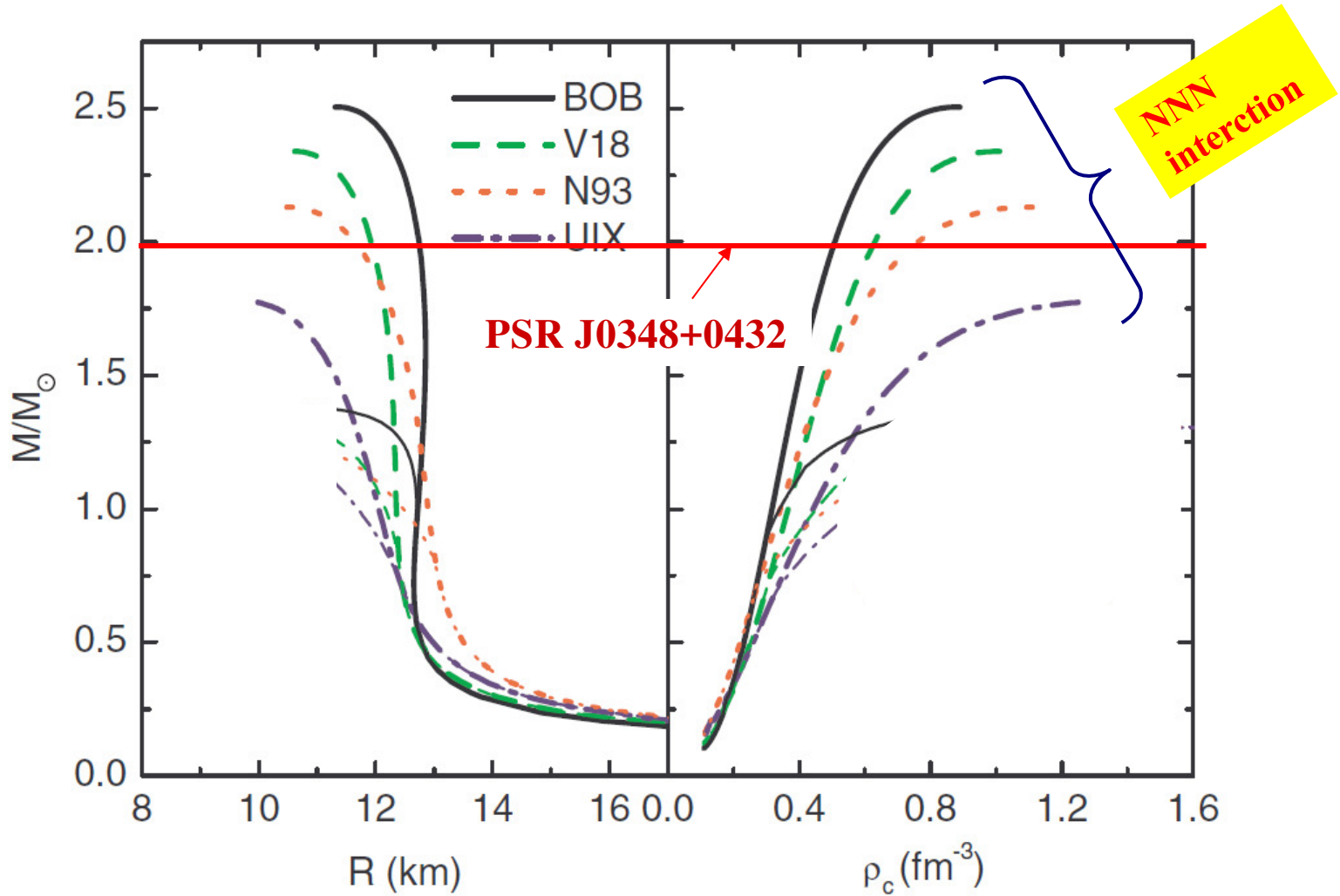
Microscopic EOS for nuclear matter: Brueckner-Bethe-Goldstone theory

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

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

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

$$\tilde{E}(n_n, n_p) \equiv \frac{E}{A} = \frac{1}{A} \left\{ \sum_{\tau} \sum_k \frac{\hbar^2 k^2}{2M} + \frac{1}{2} \sum_{\tau} \sum_k U_{\tau}(k) \right\} \quad \begin{aligned} n_n &= \frac{1}{2}(1+\beta)n \\ n_p &= \frac{1}{2}(1-\beta)n \end{aligned}$$



$\rho_{Y\text{-thr}}$ 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**

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

but the presence of hyperons in
the star seems unavoidable:
hyperon puzzle problem

Microscopic approach to hyperonic matter EOS

input

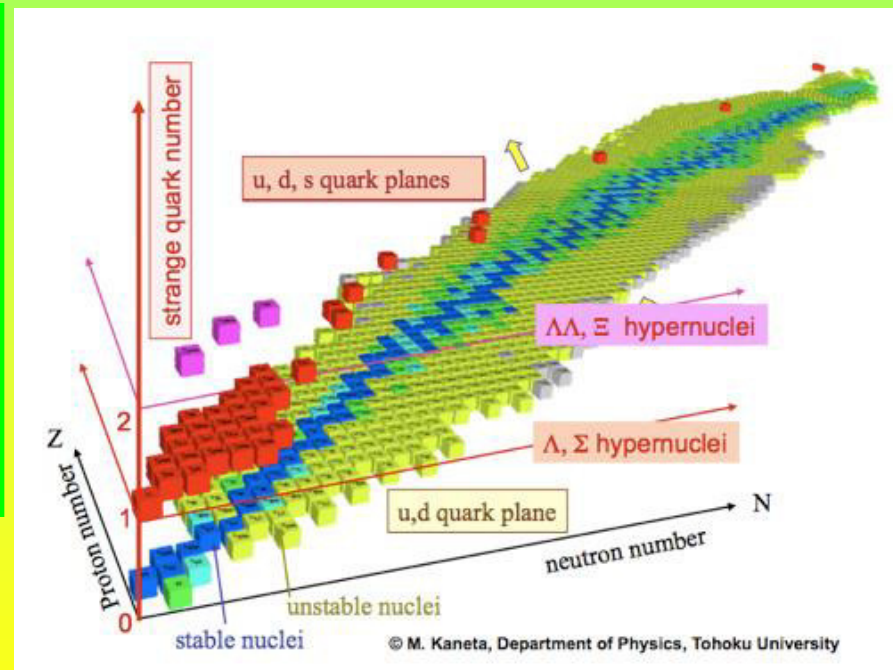
2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)

e.g. Nijmegen, Julich models

3BF: NNN, NNY, NYY, YYY

Hyperonic sector: experimental data

- 1. YN scattering data ≈ 50**
(NN data ≈ 4300)
- 2. Hypernuclei : $\approx 40 \Lambda X$, $\approx 5 \Lambda\Lambda X$**
(nuclei ≈ 3300)



Microscopic EOS for hyperonic matter: **extended Brueckner theory**

$$G(\omega)_{B_1 B_2 B_3 B_4} = V_{B_1 B_2 B_3 B_4} + \sum_{B_5 B_6} V_{B_1 B_2 B_5 B_6} \frac{Q_{B_5 B_6}}{\omega - e_{B_5} - e_{B_6}} G(\omega)_{B_5 B_6 B_3 B_4}$$

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

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

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

(**n, p, Λ , Σ^- , Σ^0 , Σ^+ , Ξ^- , Ξ^0**)

● Energy per baryon in the BHF approximation

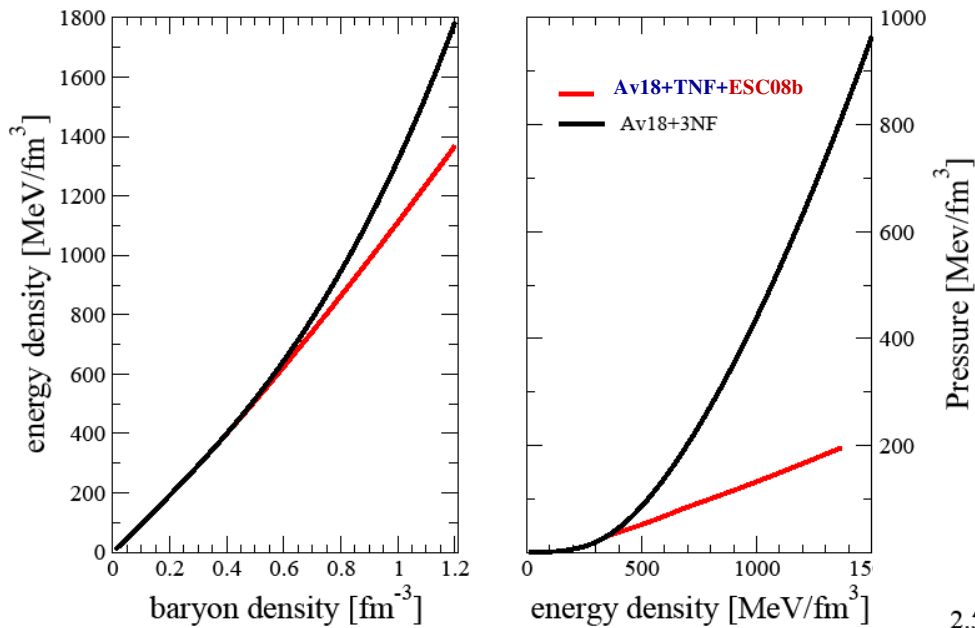
$$E/N_B = 2 \sum_{B_i} \int_0^{k_{F[B_i]}} \frac{d^3 k}{(2\pi)^3} \left\{ M_{B_i} c^2 + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} U_{B_i}^N(k) + \frac{1}{2} U_{B_i}^Y(k) \right\}$$

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



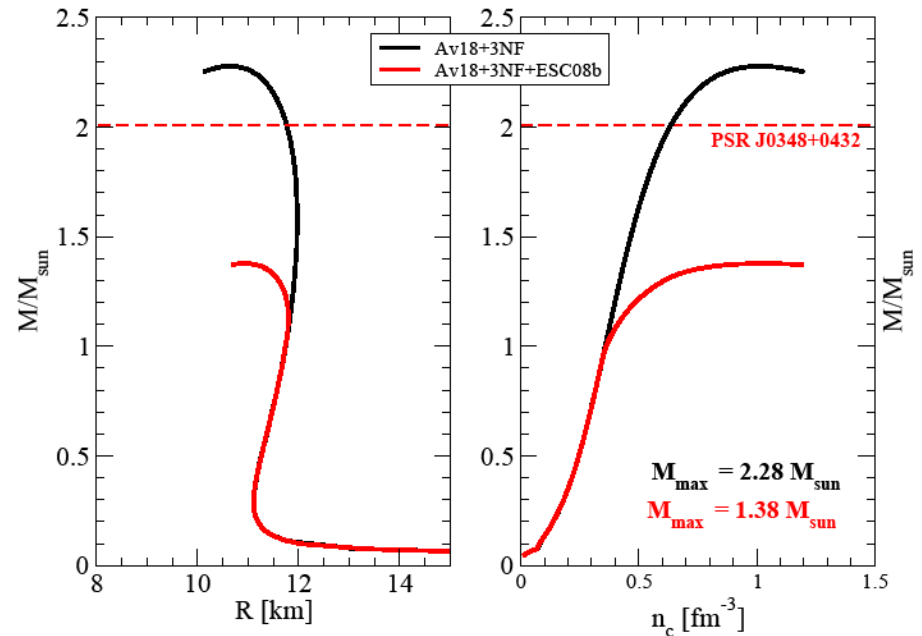
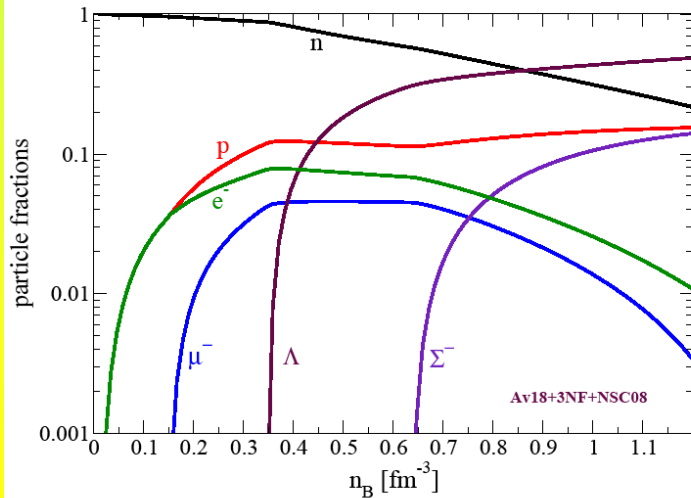
BHF
Av18 + TNF + ESC08b
no hyperonic TBF

D. Logoteta, I. Bombaci (2014)

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

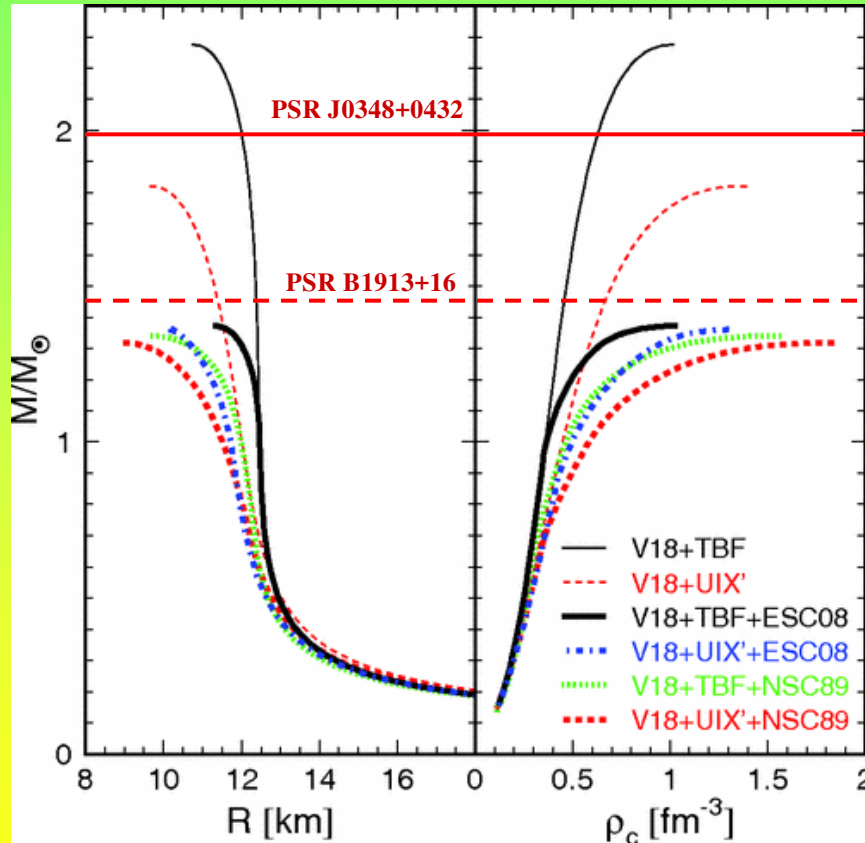
Stellar mass

Particle fractions



The stellar mass-radius relation

NN(Av18) + NNN + NY(ESC08 or NSC89)
no YY int. no hyperonic TBF



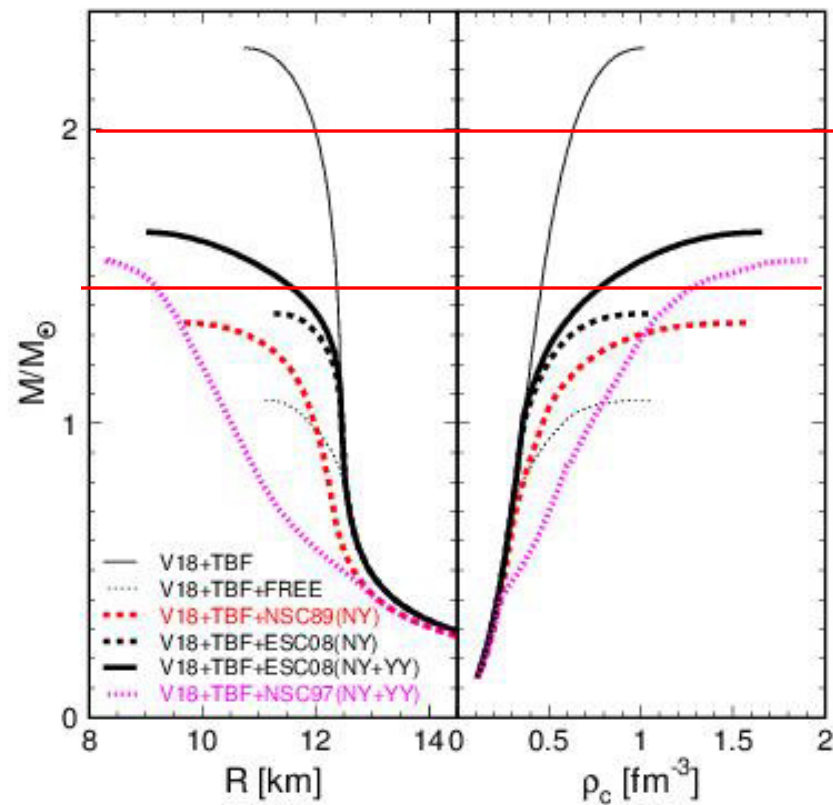
H.-J. Schulze, T. Rijken, Phys. Rev. C 84 (2011) 035801

The stellar mass-radius relation

Effect of the YY interaction TBF

NN(Av18) + NNN + NY + YY (ESC08c)

no hyperonic TBF



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 overestimate 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 and YN scattering

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

YNN three-body forces in hypernuclei

R. Spitzer, Phys. Rev. 110 (1958) 1190

G. G. Bach, Nuovo Cimento XI (1959) 73

R.H. Dalitz, 9th Int. Ann. Conf. On High Energy Physics, Ac. Sci. URSS, vol I (1960) 587

A. Bodmer, S. Sampanthar, Nucl. Phys. 31 (1962) 251

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

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

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

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

we assume:

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

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

empirical saturation point of symmetric NM

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

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

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

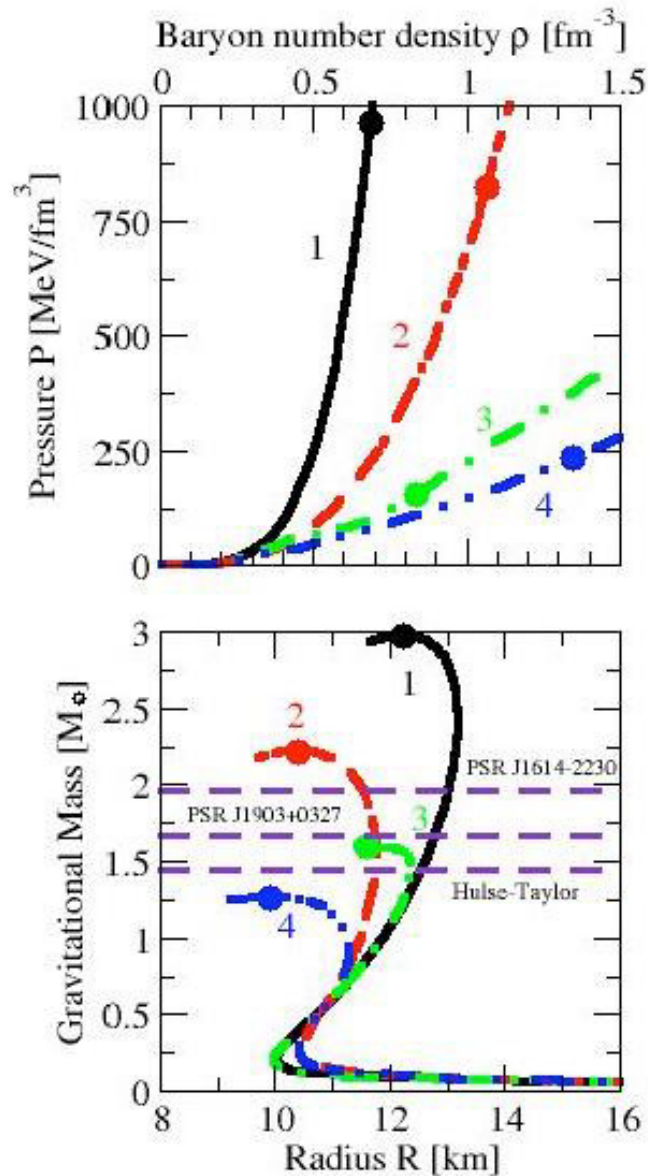
$$a_{NN}, b_{NN}, \gamma_{NN}$$

Binding energy of Λ in NM

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

$$\gamma_{NY}$$

effect of hyperonic TBF on the maximum mass of neutron stars



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

Miscroscopic hyperonic TBF

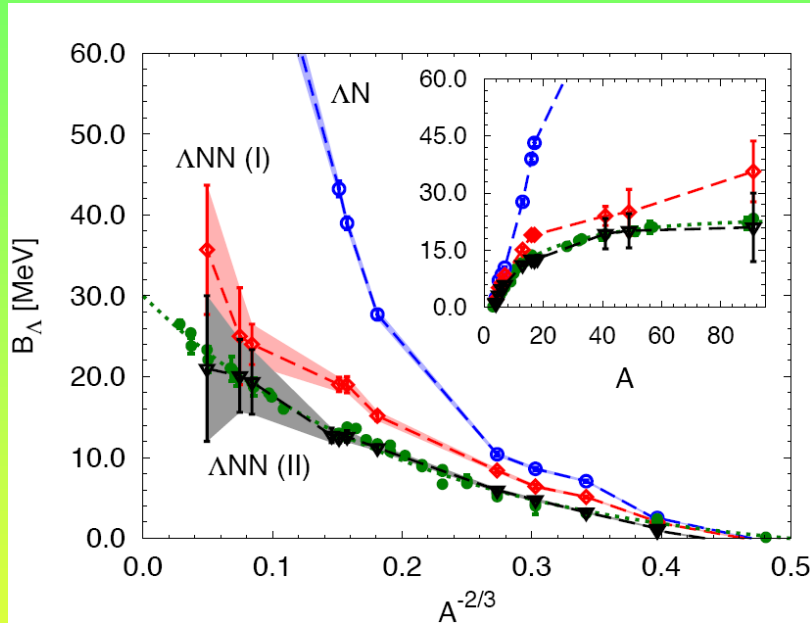
Two-meson exchange NNY potential

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

NN, NY, YY, NNN, NNY, NYY, YYY, ... interactions from Chiral Effective Field Theory

J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24
S. Petschauer, N. Kaiser, Nucl. Phys A916 (2013) 1
S. Petschauer, et al., Eur. Phys. J. 52 (2016) 15

Microscopic EOS for hyperonic matter: **AFDM**



(n, Λ) - matter

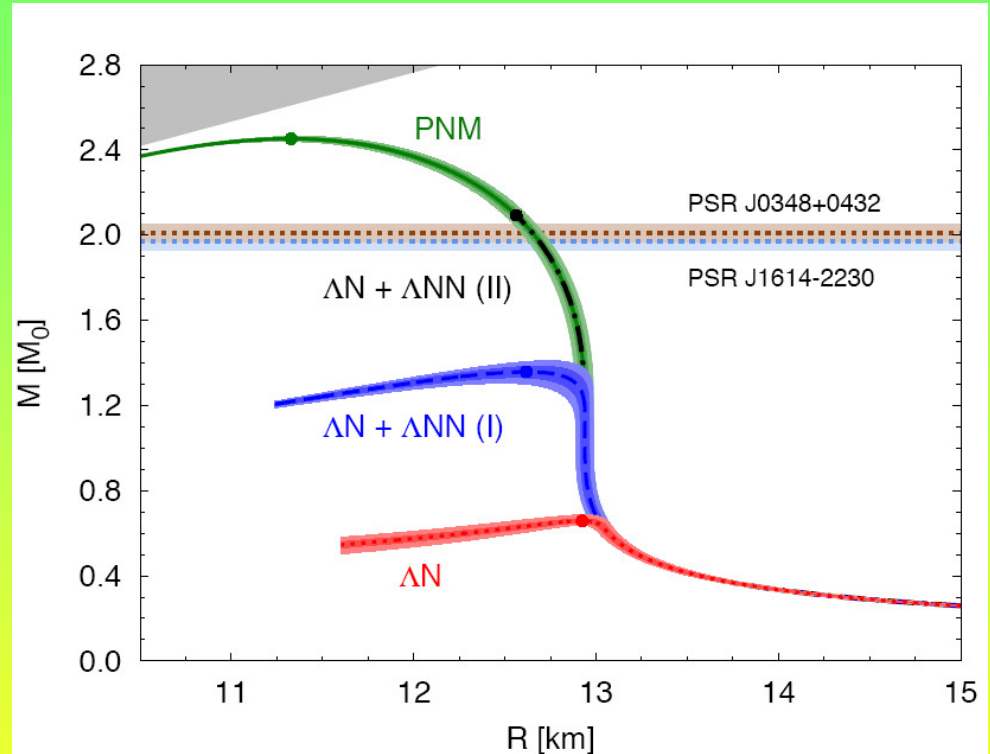
Av8' + UXI + ANN

Repulsive ANN

(Bodmer, Usmani, Carlson, 1984)

Parameters fixed to fit

B_{Λ} Λ hypernuclei ($A \leq 91$)

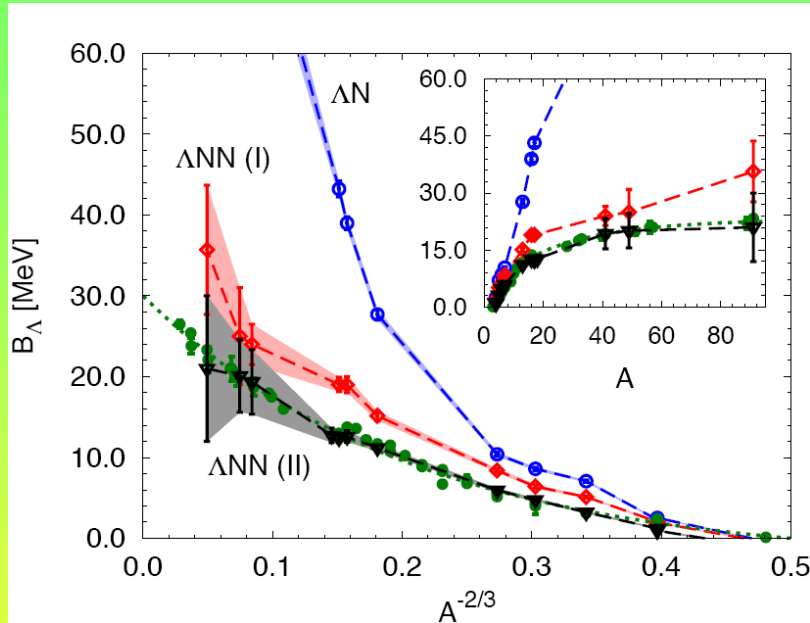


D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva, Phys. Rev. Lett. 114 (2015) 092301

**Hypernuclei can not constrain
YNN interactions at high density**

Microscopic EOS for hyperonic matter: **AFDM**

Lonardonì's talk in this session



(n, Λ) - matter

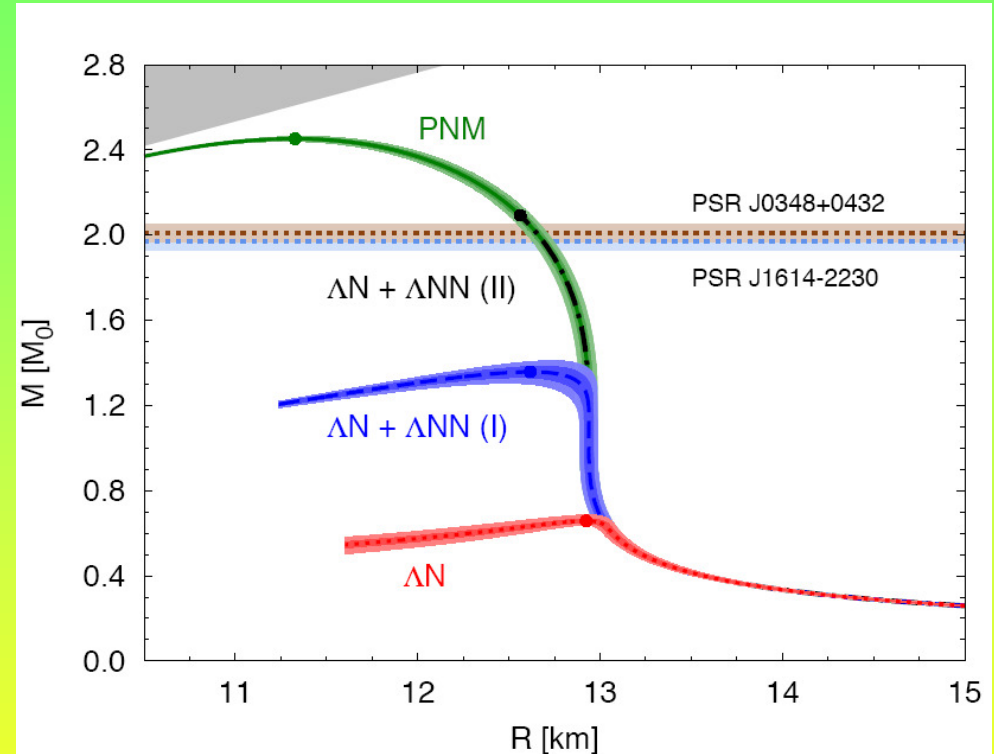
Av8' + UXI + ANN

Repulsive ANN

(Bodmer, Usmani, Carlson, 1984)

Parameters fixed to fit

B_Λ Λ hypernuclei ($A \leq 91$)



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

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 (“ $\sigma\omega\rho$ ” model)
- inclusion of vector mesons with hidden strangeness (ϕ meson)

❑ **density dependent coupling constants**

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

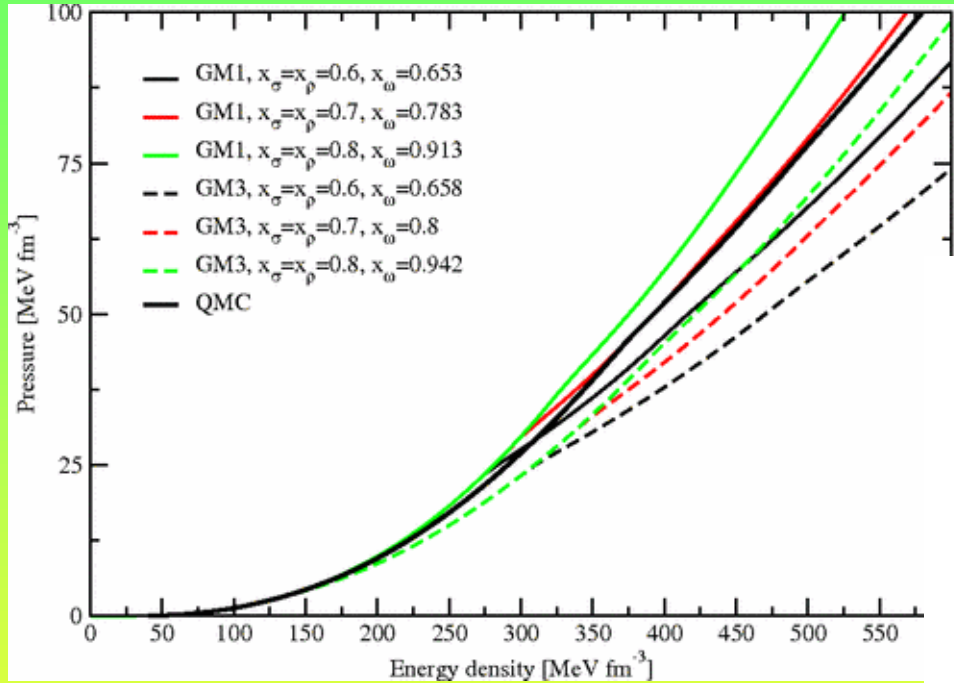
A. Taurines, C. Vasconcellos, M. Malheiro, M. Chiapparini, Mod. Phys. Lett. A 15 (2000) 1789

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



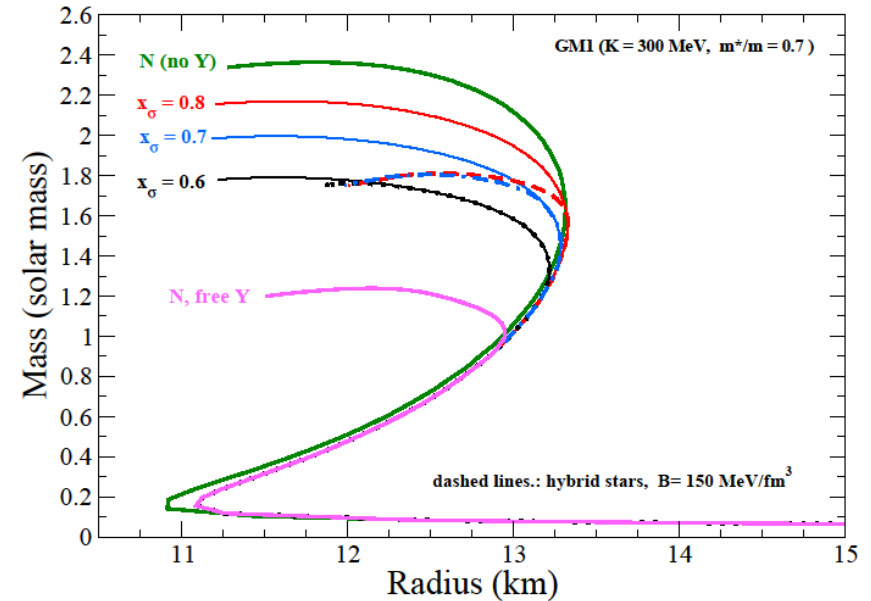
$$g_{\sigma Y} = x_\sigma g_{\sigma N}$$

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

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

$$x_\rho = x_\sigma$$

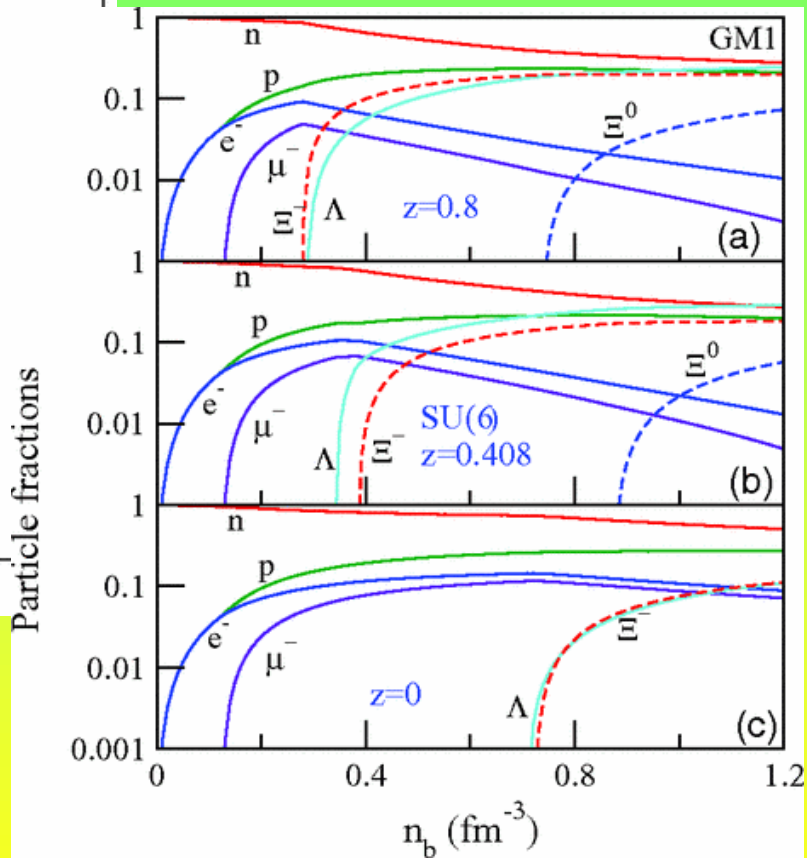
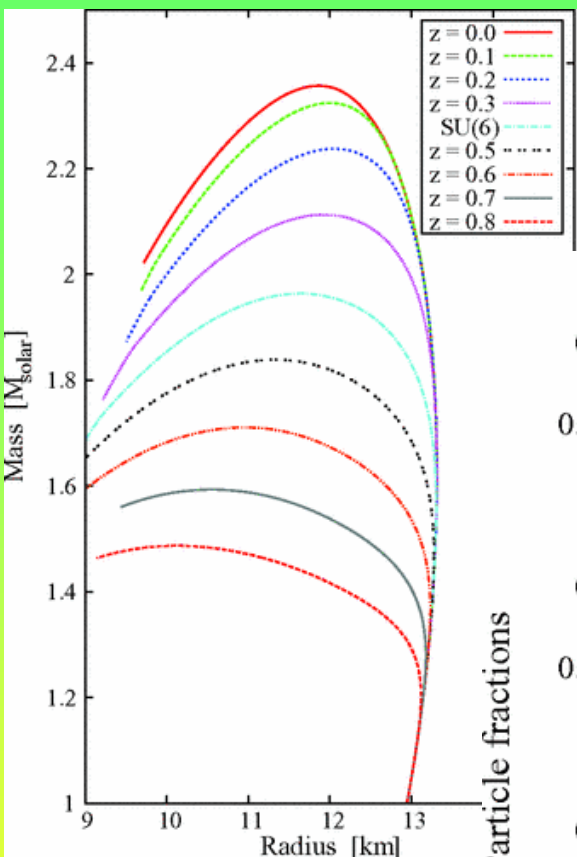
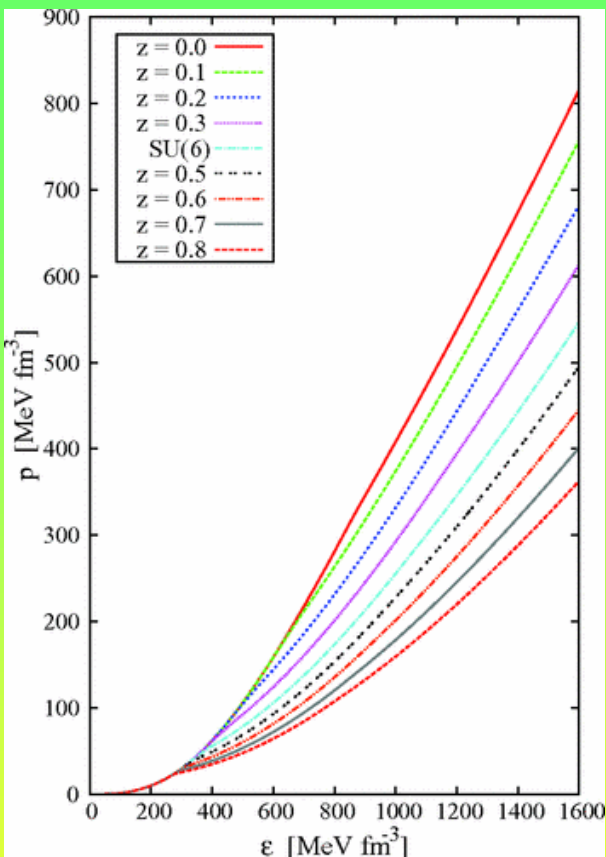
I. Bombaci, P.K. Pandha, C. Providencia, I. Vidana,
Phys. Rev. D 77 (2008) 083002



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 $\mu_b=0$ 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

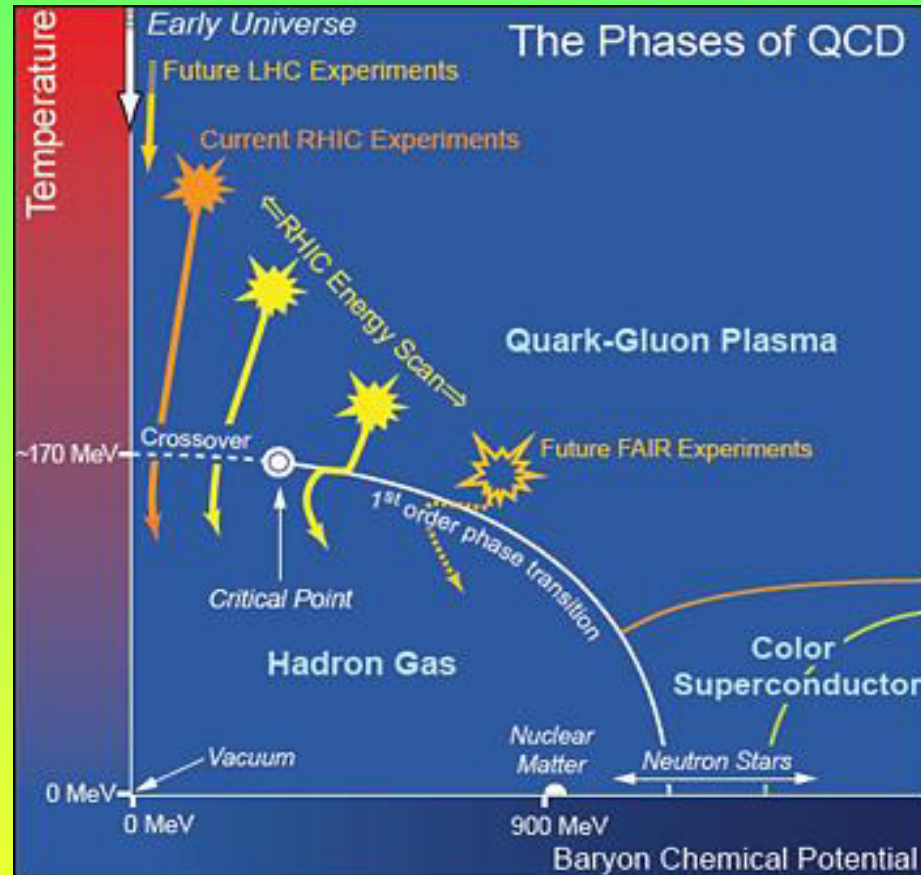
$$T_c = 154 \pm 9 \text{ MeV}$$

Bazarov et al., *Phys.Rev. D*85 (2012) 054503

Wuppertal-Budapest Collab.

$$T_c = 147 \pm 5 \text{ MeV}$$

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

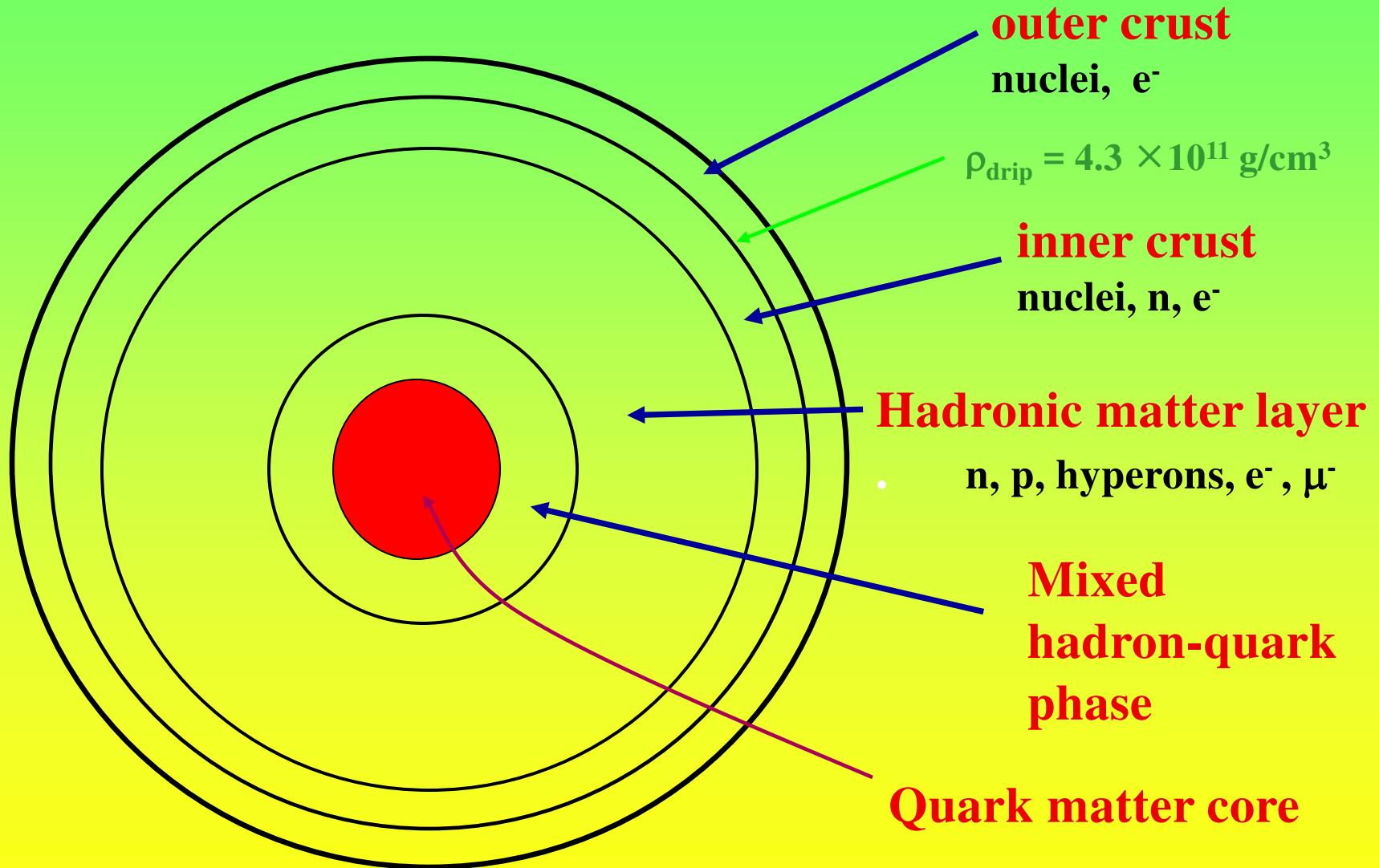
Quark deconfinement transition expected of the first order

Z. Fodor, S.D. Katz, *Prog. Theor. Suppl.* 153 (2004) 86

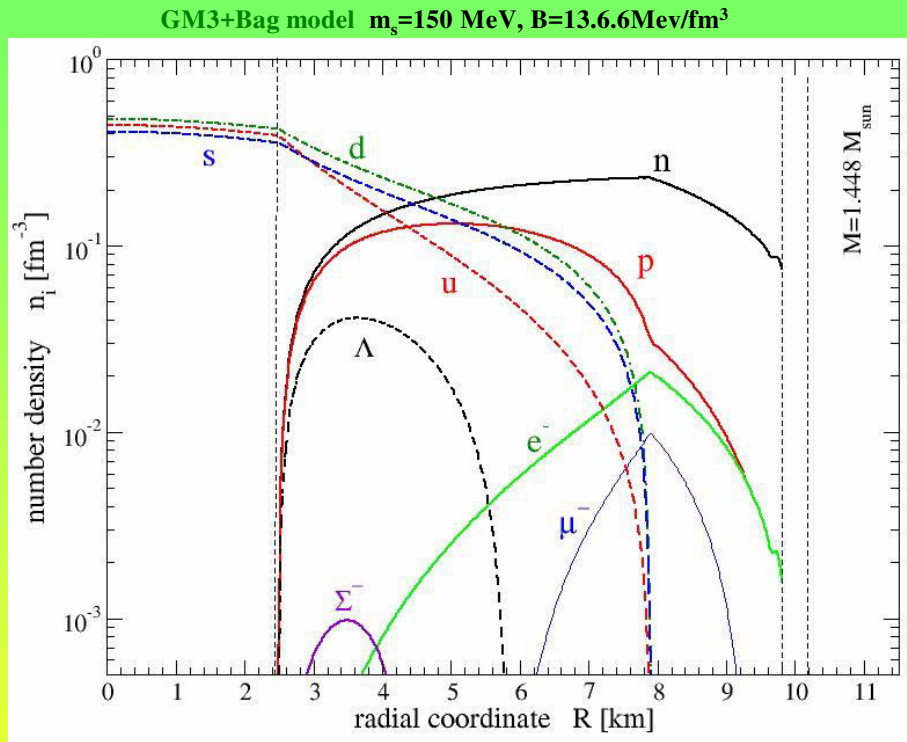
“A link between lattice QCD and measured neutron star masses”

I. Bombaci, D. Logoteta, *Mont. Not. Royal Astron. Soc.* 433 (2013) L79

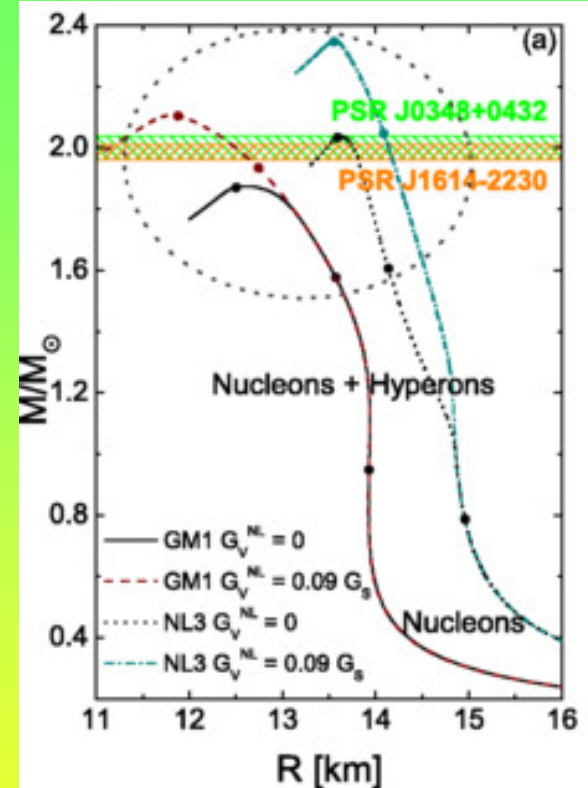
Hybrid Stars (neutron stars with a quark matter core)



Hybrid Stars (neutron stars with a quark matter core)



I. Bombaci, I. Parenti, I. Vidaña (2004)



M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, Phys. Rev. C 89 (2014) 015806

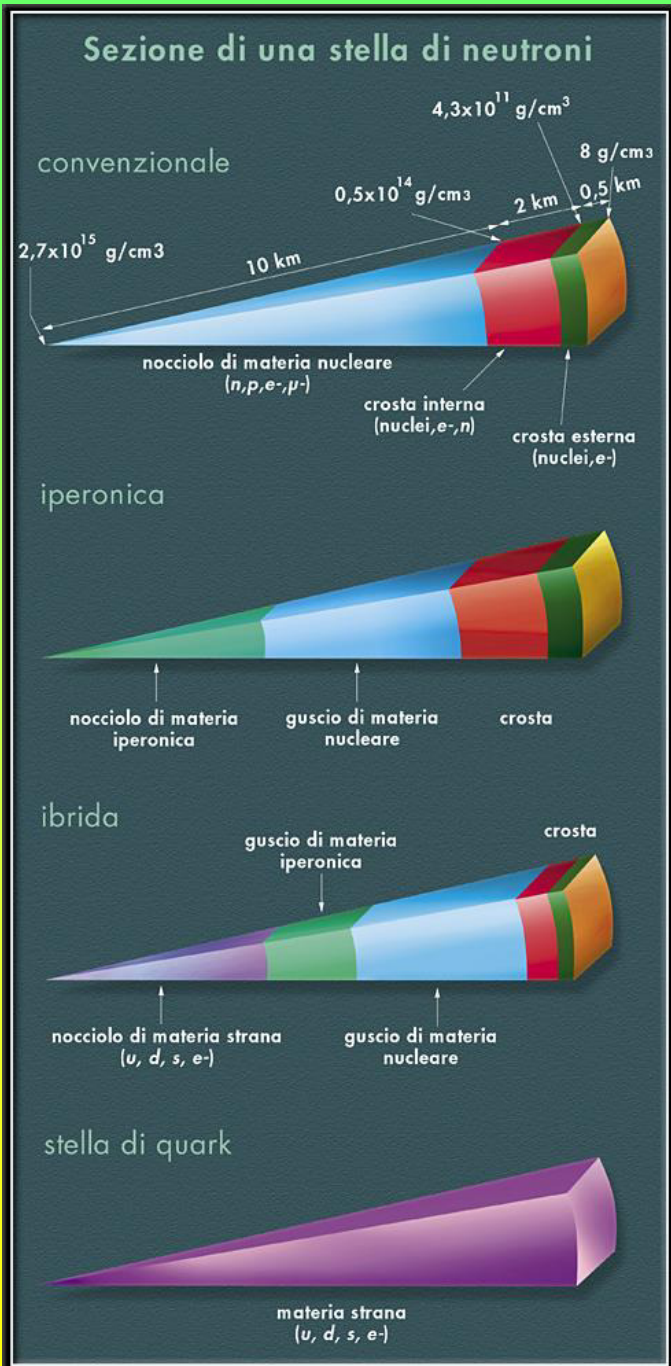
perturbative QCD calculations up to α_s^2

A. Kurkela et al., Phys. Rev. D 81, (2010) 105021

M_{max} up to $\sim 2 M_{\odot}$

Present measured NS masses do not exclude the possibility of having QM in the stellar core

“Neutron Stars”



Nucleon Stars

Hyperon Stars

Hadronic Stars

Hybrid Stars

Strange Stars

Quark Stars

Quark matter nucleation in Neutron 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

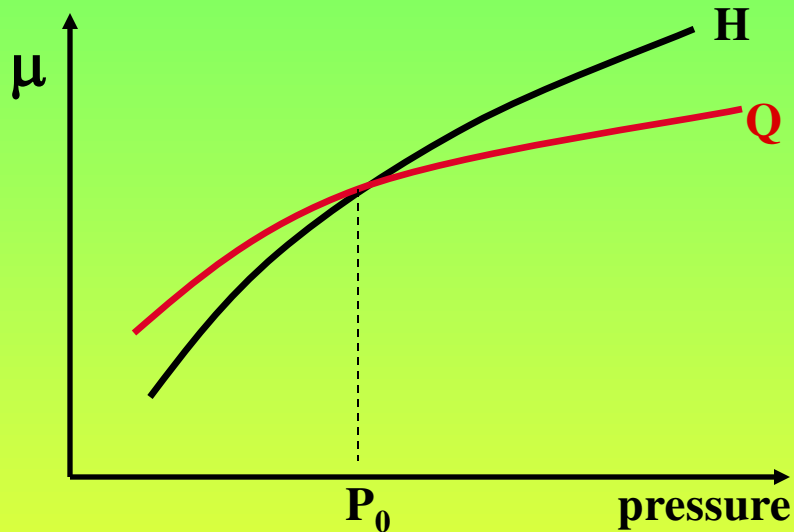
Virtual drops of the stable phase are created by small localized **fluctuations** in the state variables of the **metastable phase**



A common event in nature, e.g.:

- **fog or dew formation in supersaturated vapor**
- **ice formation in supercooled water**

Pure and distilled water at standard pressure (100 kPa) can be supercooled down to a temperature of -48.3 C. In the temperature range $(-48.3 - 0)$ C, water is in a metastable phase and ice crystals will form via a nucleation process.



In NS cores when $P_{\text{centr}} = P(r=0) > P_0$

Hadronic matter phase is metastable

The **stable Quark matter phase** formed by a **nucleation process**

Gibbs' criterion for phase equilibrium

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

$$T_H = T_Q \equiv T$$

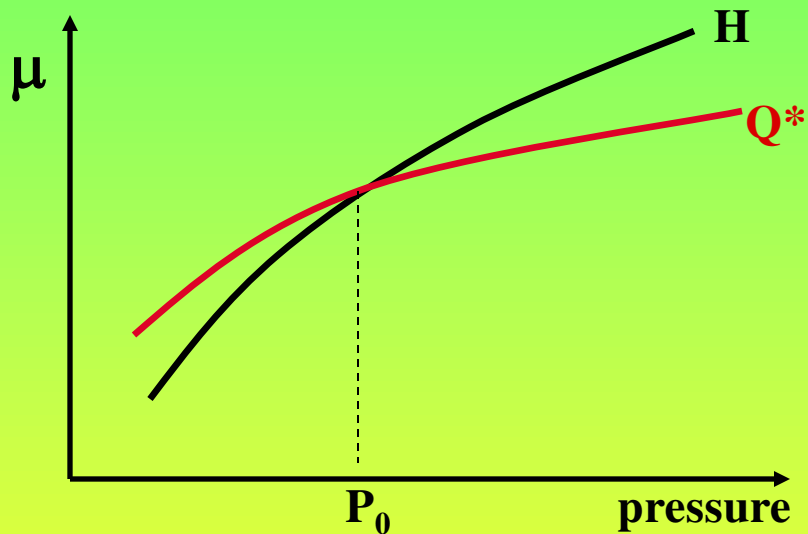
$$P(\mu_H) = P(\mu_Q) \equiv P(\mu_0) \equiv P_0$$

μ_j = Gibbs' energy per baryon
(j-phase average chemical pot.) $j = H, Q$

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

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

Hadronic Stars with $P_{\text{centr}} > P_0$ are **metastable**
to the **conversion** to **Quark Stars**



First drop of Q^* -matter

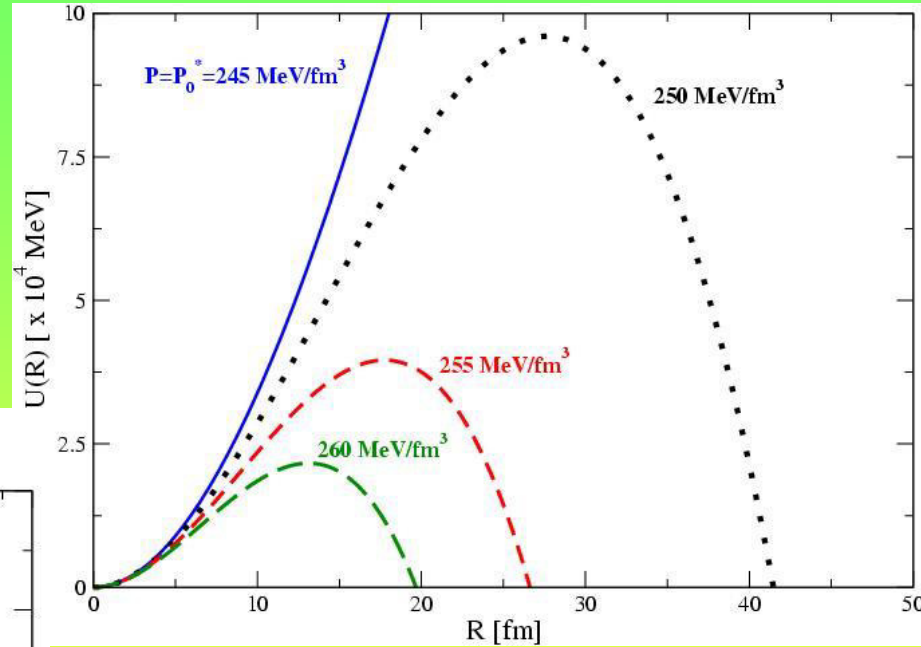
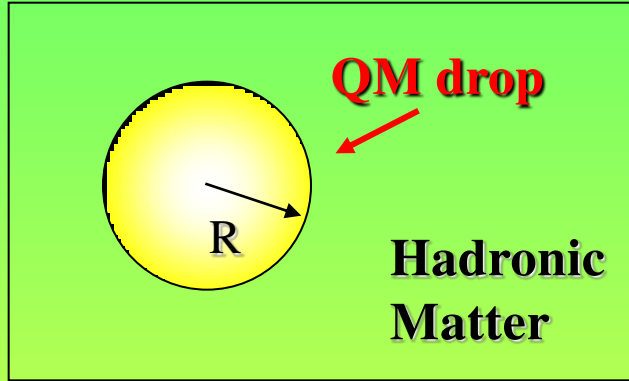


stellar conversion process
HS \rightarrow QS

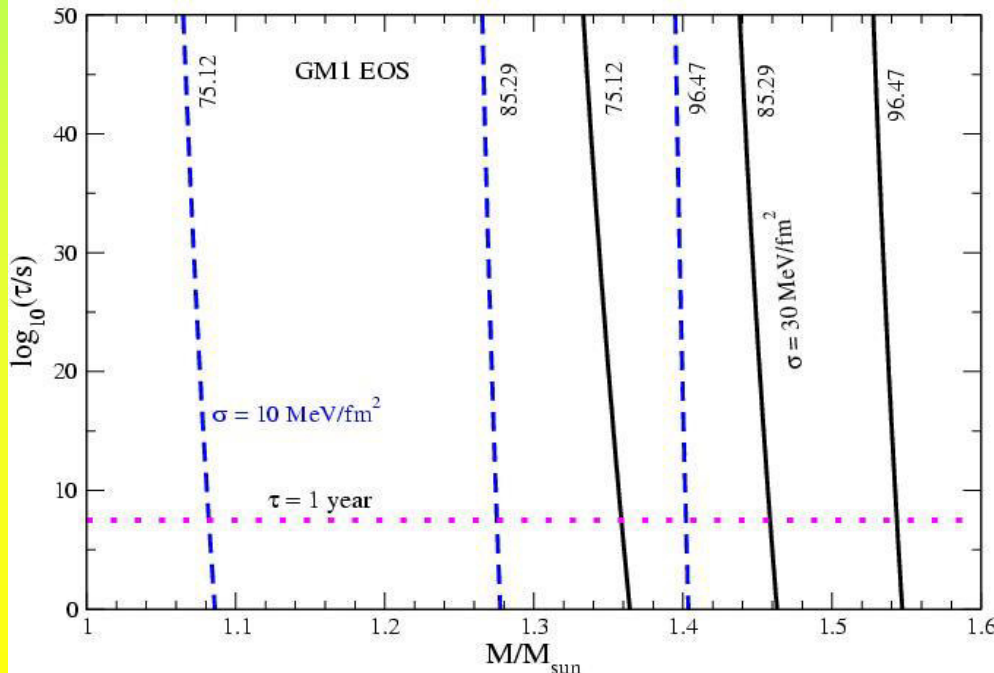
The **mean lifetime** of the metastable Hadronic Star configuration is related to **nucleation time** of the first drop of **Q^* -phase**

Quantum nucleation theory

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



Hadronic Star mean-life time



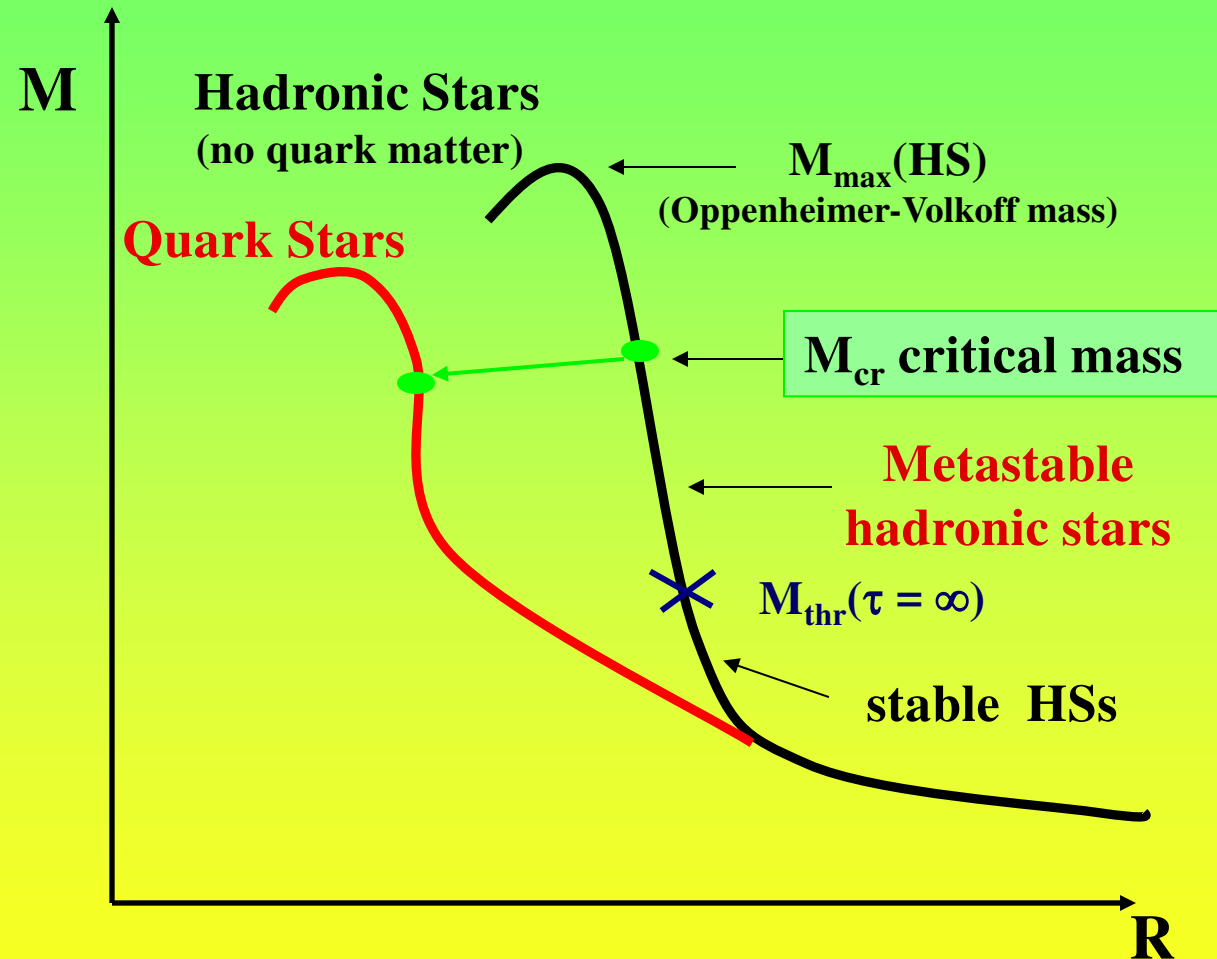
$$U(R) = (4/3)\pi R^3 n_{Q^*} (\mu_{Q^*} - \mu_H) + 4\pi\sigma R^2$$

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

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

- Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. 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
I. Bombaci, P.K. Panda, C. Providencia, I. Vidaña, *Phys. Rev. D* **77** (2008) 083002
I. Bombaci, D. Logoteta, P.K. Panda, C. Providencia, I. Vidaña, *Phys. Lett. B* **680** (2009) 448
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, *Astr. and Astrophys.* **528** (2011) A71
I. Bombaci, D. Logoteta, I. Vidaña, C. Providencia, *EPJ A* **52** (2016) 58

Metastability of Hadronic Stars



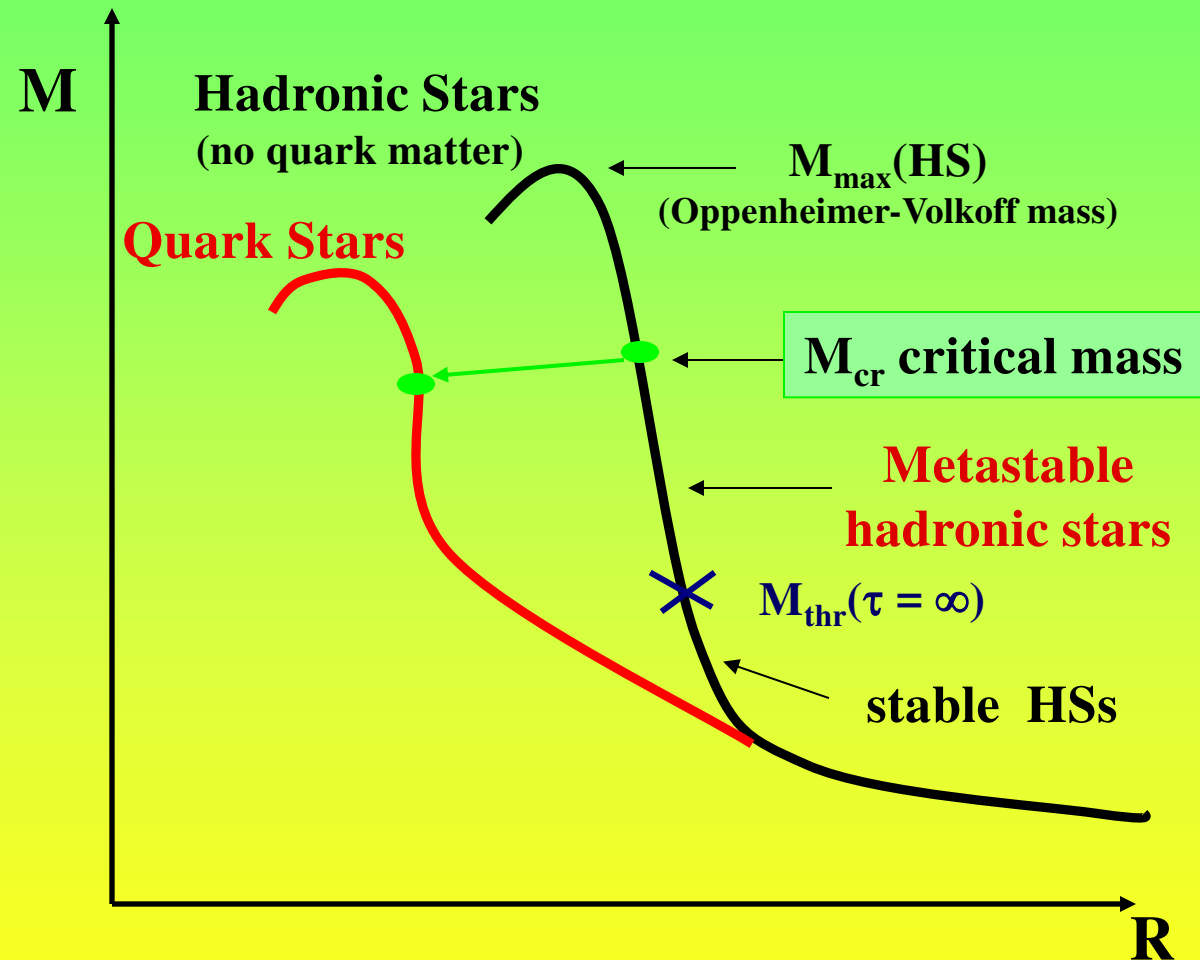
Hadronic Stars above a threshold value of their gravitational mass are metastable to the **conversion** to **Quark Stars (QS)** (hybrid stars or strange stars)

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



- M_{cr} , critical mass of hadronic stars.

- Two branches of compact stars

- stellar conversion $\text{HS} \rightarrow \text{QS}$

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

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

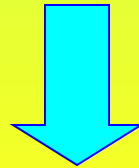
extension of the concept of limiting mass of compact stars with respect to the *classical* one given by Oppenheimer and Volkoff

The critical mass of metastable Hadronic Stars

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

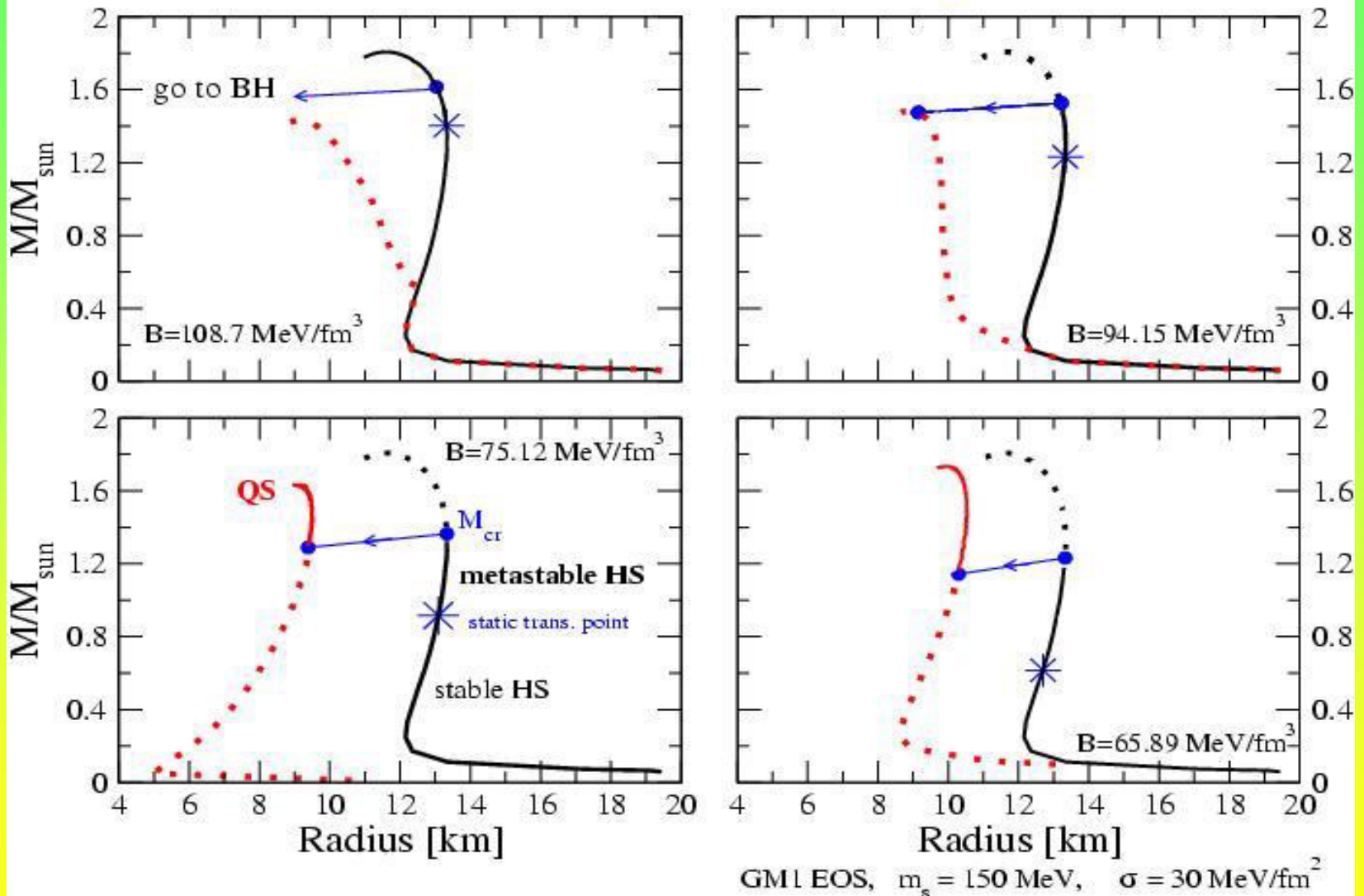
- HS with $M_{\text{thr}} < M_{\text{HS}} < M_{\text{cr}}$ are metastable with $\tau = 1 \text{ yr} \div \infty$

- HS with $M_{\text{HS}} > M_{\text{cr}}$ 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

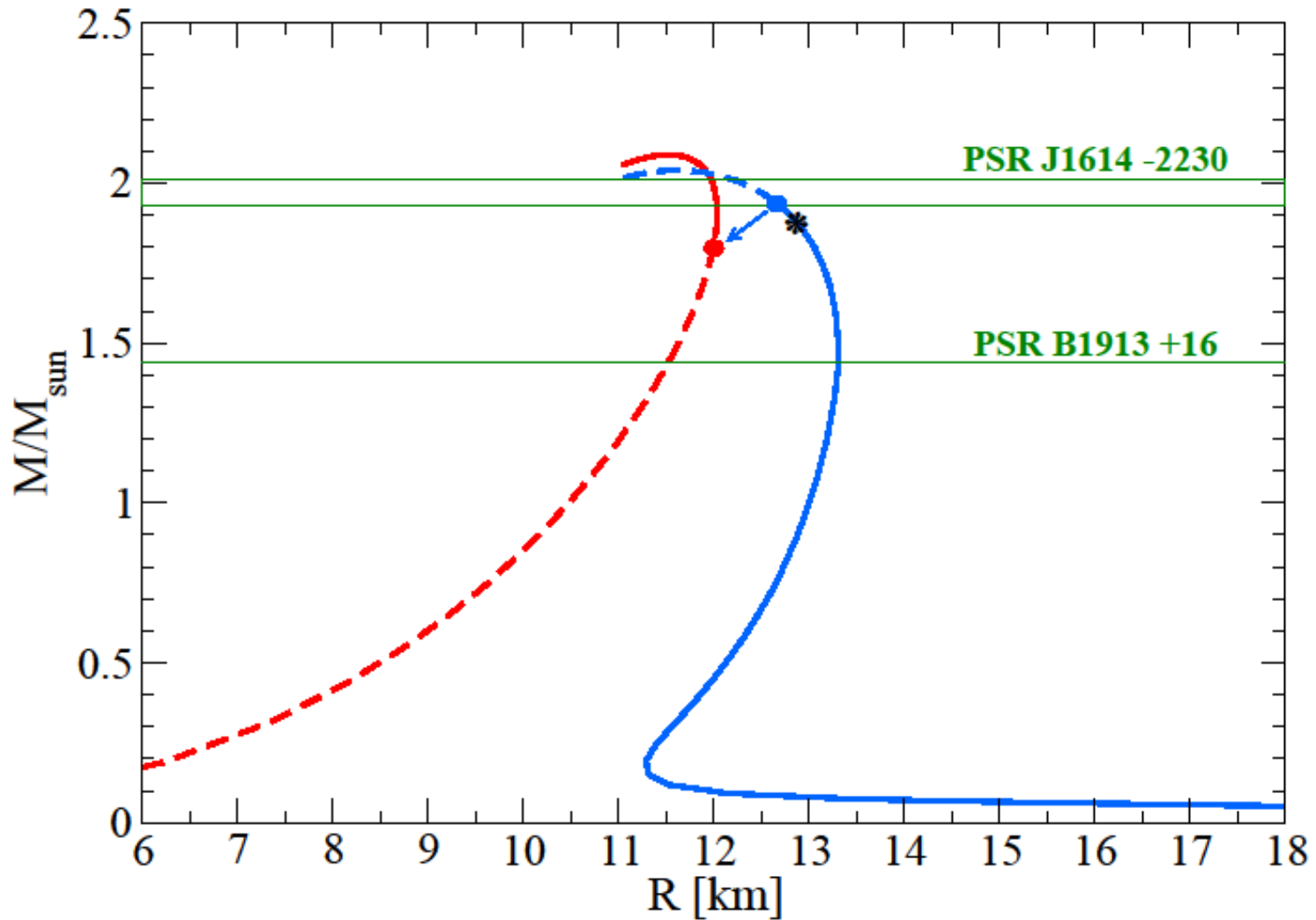
The two families of Compact Stars



Hadronic Stars: nucleons + hyperons

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

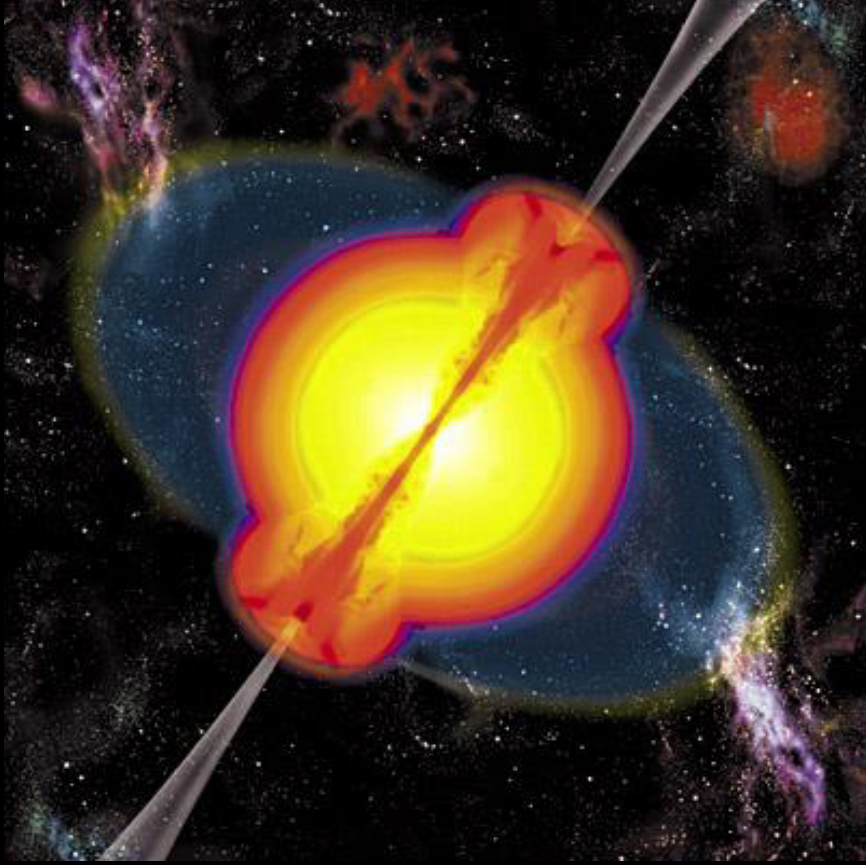
The two families of compact stars



I. Bombaci, et al. EPJ A 52 (2016) 58

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

Total energy released in the stellar conversion

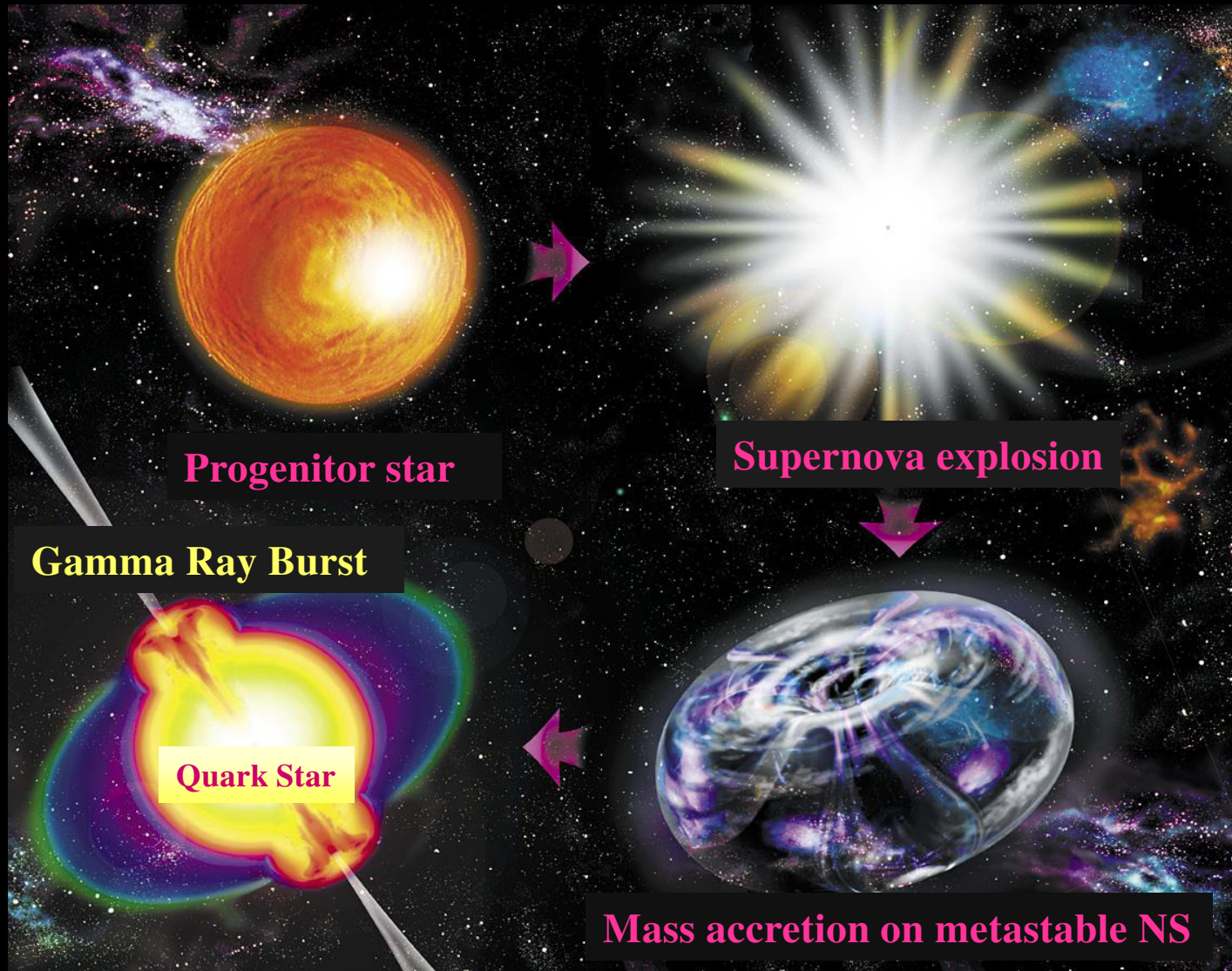


Assuming that the **stellar baryonic mass is conserved** during the stellar conversion, the total energy released in the process is :

$$E_{\text{conv}} = M_{\text{cr}} - M_{\text{QS}}(M_{\text{cr}}^{\text{b}})$$
$$\sim 10^{53} \text{ erg}$$

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

Supernova-GRB connection: Hadronic Star \rightarrow Quark Star conversion model



Summary

“**Hyperon puzzle**” in Neutron star physics $M_{\max} < 2 M_{\odot}$ \rightarrow

\rightarrow 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)

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

The parameters regulating the strength of these interactions can not be fully constrained by the present experimental data on YN scattering and hypernuclei. Thus, fixing these parameters to obtain hyperon stars with $M_{\max} > 2 M_{\odot}$ corresponds, in some sense, to an *ad hoc* condition and not to a genuine solution of the hyperon puzzle.

(ii) or, the transition to **Strange Quark Matter** produce a stiffening

of the EOS due e.g. to perturbative quark interactions

NS \rightarrow Quark Stars (hybrid or strange stars)

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