The ExtreMe Matter Institute (EMMI)
at GSI Helmholtz Centre for Heavy Ion Research, Darmstadt
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The hyperon puzzle in Neutron Stars

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The so-called hyperon puzzle in neutron stars is the difficulty to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors.

Summary of the talk

- **Introduction to neutron star (NS) physics and results for *nucleon stars***
- **Hyperons in dense matter and the origin of the hyperon puzzle**
- **Hyperonic three-body interactions as a possible solution of the hyperon puzzle**
- **Strange quark matter in NSs and hyperon puzzle**

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

$\rho_0 = 2.6 \times 10^{14}$ g/cm^3 ($n_0 \sim 0.16$ fm^{-3} nuclear saturation density)

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

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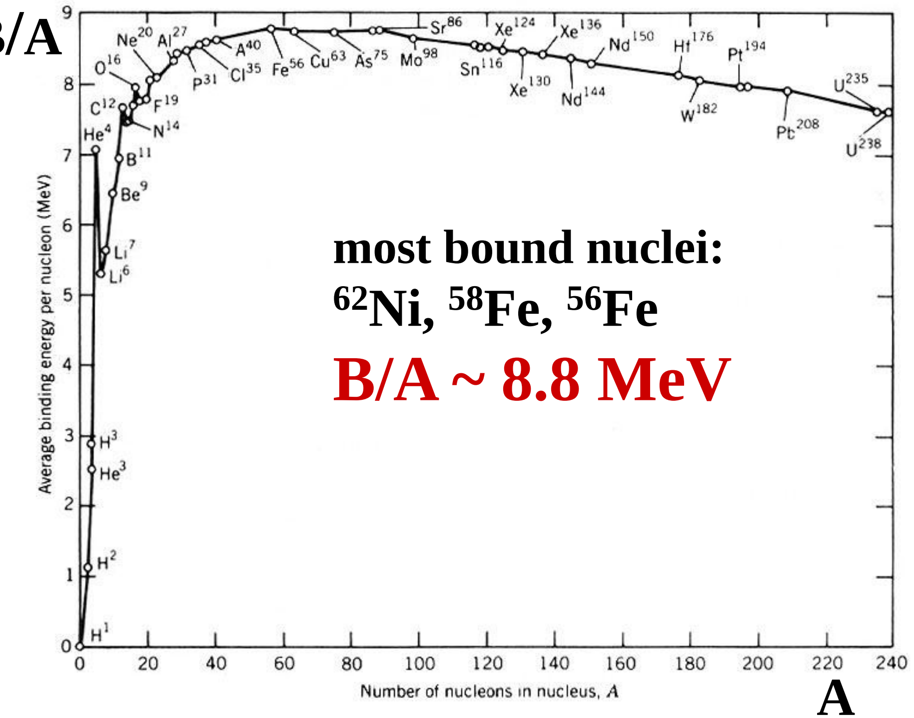
Atomic Nuclei: bulk properties

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

Radius $R = r_0 A^{1/3} \sim (2 - 8)$ fm

Density $\rho \sim \rho_0 = 2.6 \times 10^{14}$ g/cm^3

B/A



A

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

$B/(Mc^2) \sim (0.1\text{–}1)\%$

bound by nuclear interactions

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Relativistic equations for stellar structure

Static and sphericaly symmetric self-gravitating mass distribution

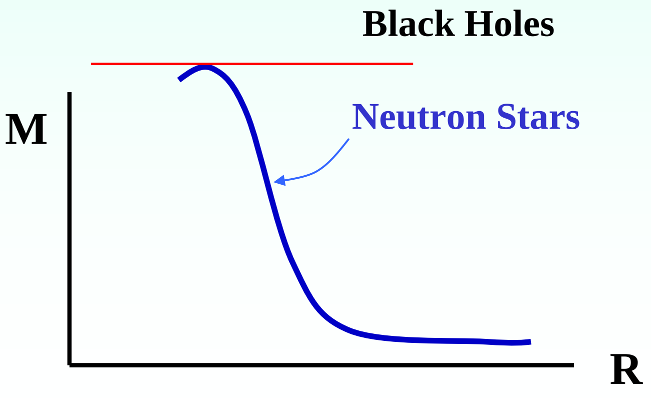
Tolman – Oppenheimer – Volkov equations (TOV)

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

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

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

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



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

Measured Neutron Star masses in relativistic binary systems: three “heavy” Neutron Stars

Measuring post-Keplerian parameters: very accurate NS mass measurements; model independent measurements within GR

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

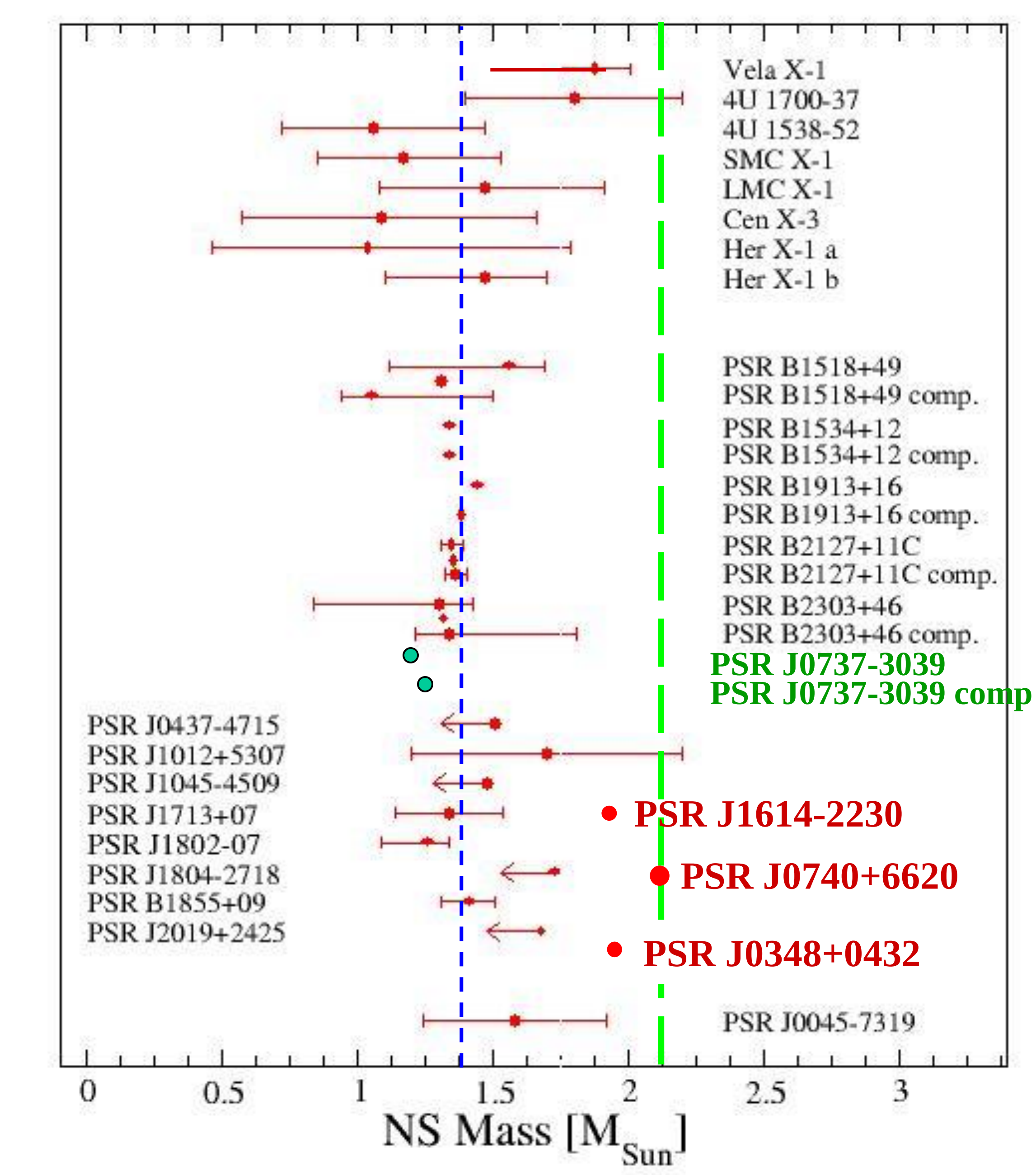
PSR J0740+6620 $M_{NS} = 2.14^{+0.10}_{-0.09}\ M_\odot$

NS – WD binary system $M_{WD} = 0.258\ M_\odot$ (companion mass)

P_b = 4.7669 days (orbital period) P = 2.89 ms (PSR spin period) $i = 87.38° \pm 0.20°$ (inclination angle)

H. T. Cromartie et al., Nature Astronomy 4 (2020) 72

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 principle**

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

$\longrightarrow$ antisymmetric wave function for particle Exchange $\rightarrow$ Pauli principle

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

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

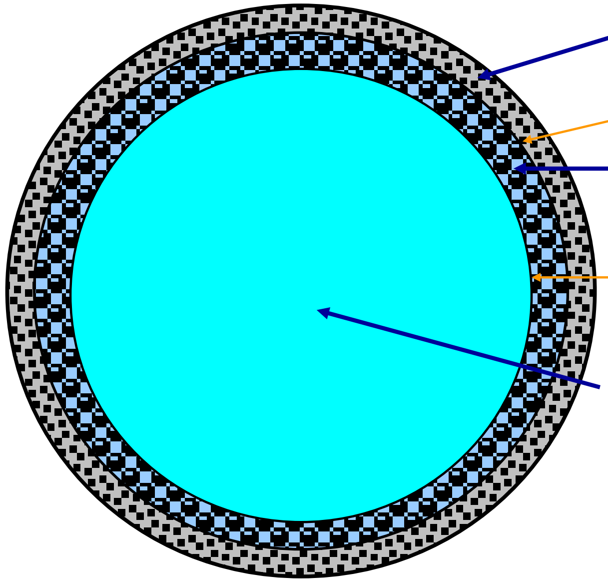
β-stable nuclear matter

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

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

$$\mu_e \geq m_\mu$$

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



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

$$\boxed{\begin{aligned} \mu_n - \mu_p &= \mu_e \\ \mu_\mu &= \mu_e \end{aligned}}$$

neutrino-free matter

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

- **Charge neutrality**

$$\boxed{n_p = n_e + n_\mu}$$

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

Microscopic approach to asymmetric nuclear matter EOS

input

Two-body nuclear interactions: V_{NN}

Parameters fitted to
NN scatering data with **χ^2/datum ~1**

Three-body nuclear interactions: V_{NNN}

Parameters fitted to

- **binding energy of A = 3, 4 nuclei** or
- **empirical saturation point of symmetric nuclear matter**:

$n_0 = (0.16 \pm 0.01)\ fm^{-3}$, $E/A = (-16 \pm 1)$ 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

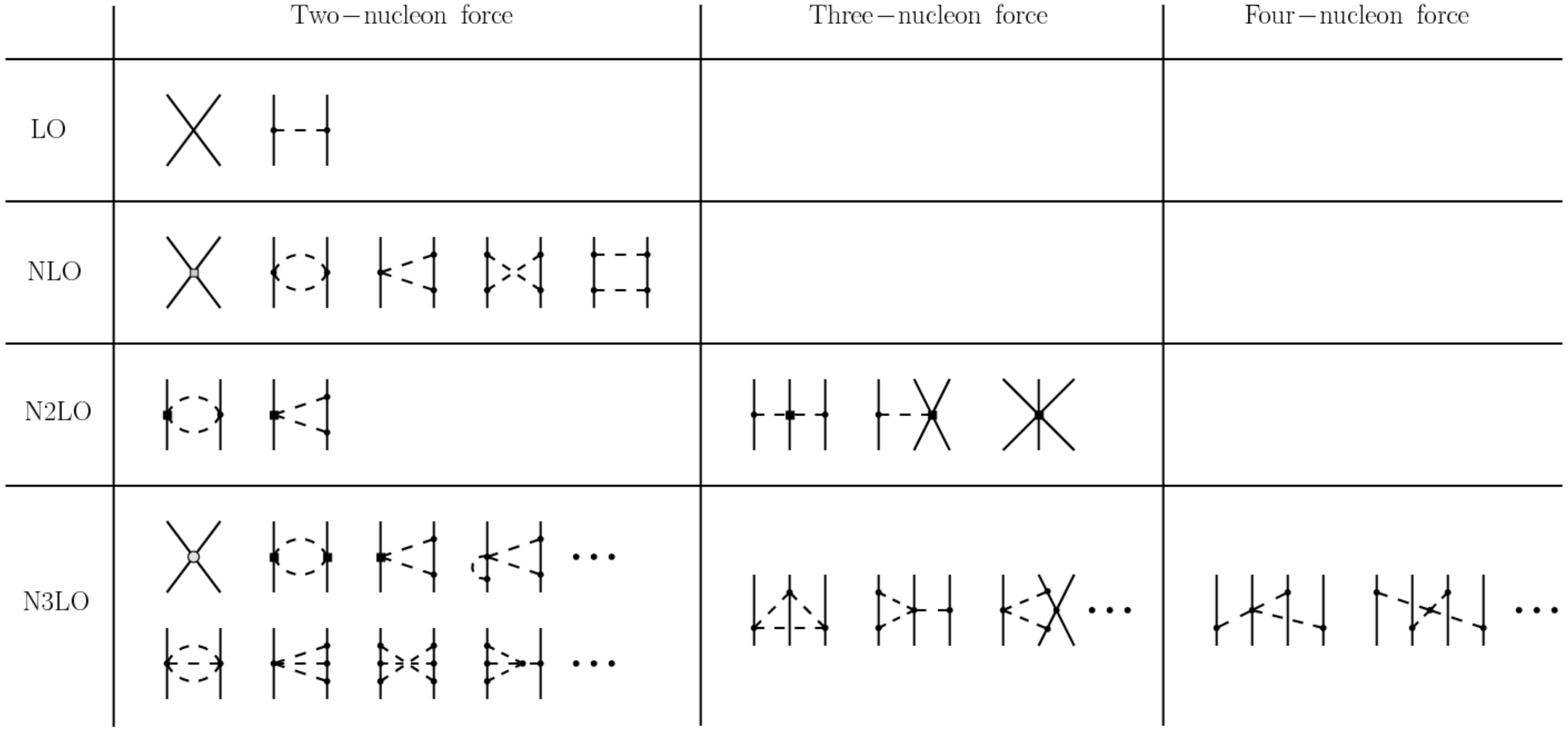
Values in MeV

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

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

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

Nuclear interactions derived in Chiral Perturbation Theory (ChPT)



Two-nucleon (NN), three-nucleon (NNN) and many-nucleon intercations can be calculated perturbatively (i.e. order by order) according to a well-defined scheme based on a low-energy effective QCD Lagrangian.

S. Weinberg, Physica A 96 (1979) 327; Phys. Lett. B 251 (1990) 288; Phys. Lett B 259 (1992) 114
E. Epelbaum, H.-W. Hammer, U. G. Meißner, Rev. Mod. Phys. 81 (2009) 1773
R. Machleidt and D. R. Entem, Phys. Rep. 503 (2011) 1
S. Petschauer, J. Haidenbauer, N. Kaiser, , U. G. Meißner, W. Weise, Front. Phys. 8 (2020) 12

A new microscopic EOS model for nuclear matter

I. Bombaci, D. Logoteta, Astron. and Astrophys. 609 (2018) A128

Available in tabular form on **CompOSE** web site
https://compose.obspm.fr/eos/120/

$V_{NN} + V_{NNN}$

↓

Quantum Many-Body Theory

↓

EOS
β-stable matter

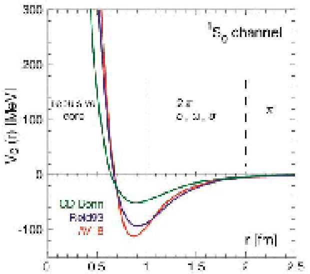
↓ TOV

Neutron Star properties

↓

observational data
(measured NS properties)

e.g.
Brueckner-Hartree-Fock
$V_{NN} \longrightarrow G_{NN}$



Quantum many-body approach

Brueckner-Bethe-Goldstone theory

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

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

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

Energy per baryon in the Brueckner-Hartree-Fock (BHF) approximation

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

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

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

Symmetric Nuclear matter

Interactions

NN ChEFT N3LO Δ(1232)

Piarulli et al., Phys. Rev. C 94 (2016) 054007

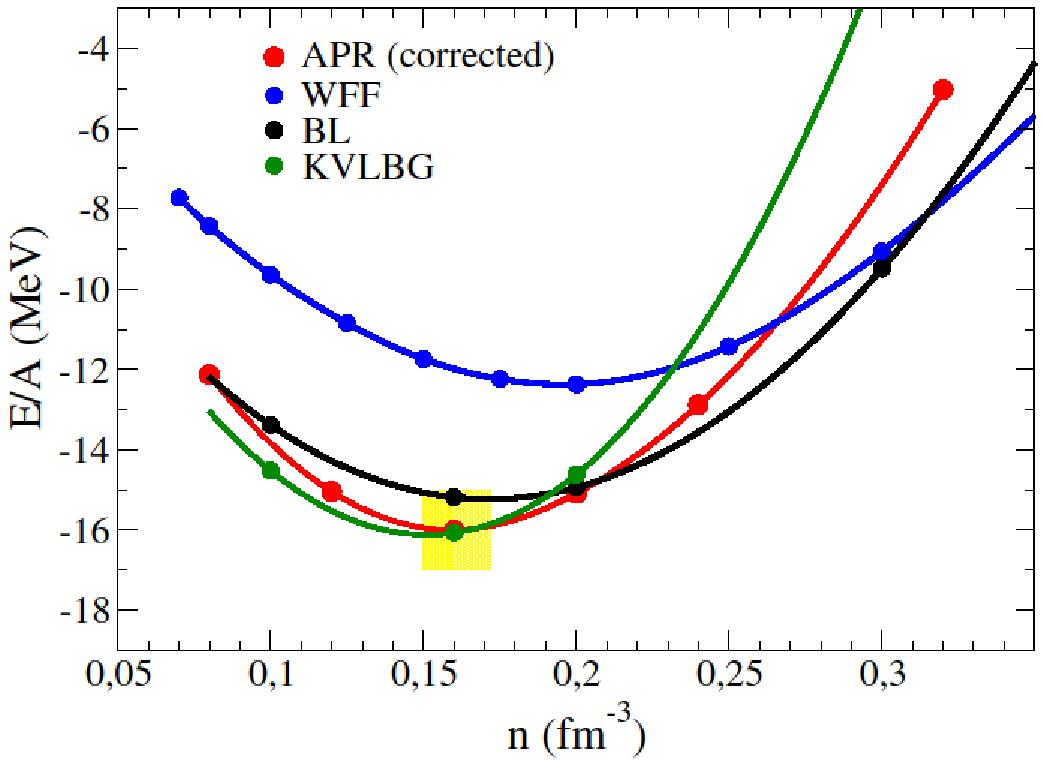
NNN ChEFT N2LO Δ(1232)

Epelbaum et al., Phys. Rev C 66 (2002) 064001

Navratil, Few-Body Syst. 41 (2007) 117

average → V^{eff}_{NN} **(n)**

Logoteta et al., Phys. Rev. C 94 (2016) 064001



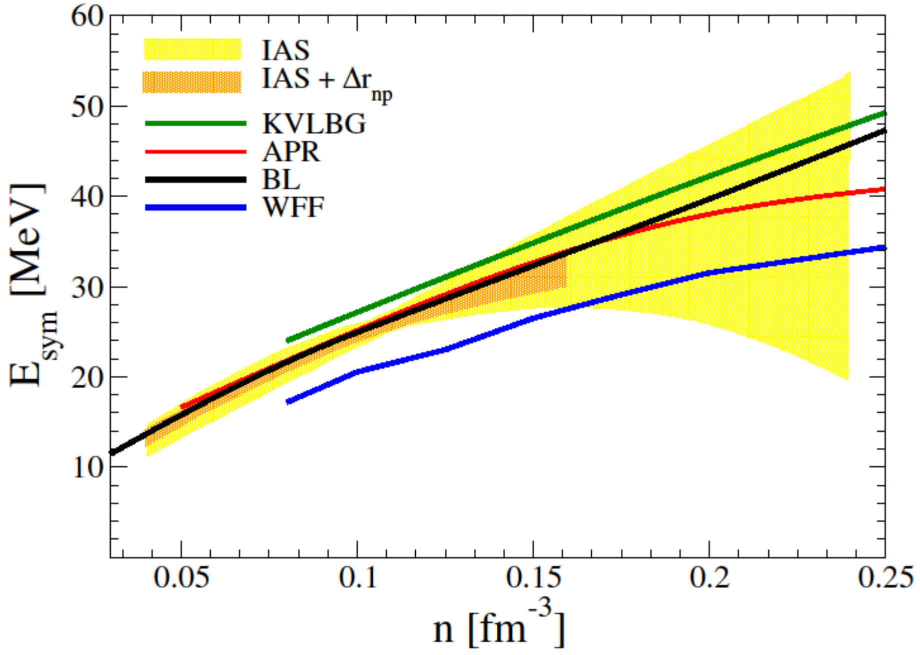
BL : I. Bombaci, D. Logoteta, Astron. and Astrophys. 609 (2018) A128

WFF : R.B. Wiringa, V. Ficks and A. Fabrocini, Phys. Rev. C **38** (1988) 1010.

APR :A. Akmal, V.R. Pandharipande and D.G. Ravenhall, Phys. Rev. C **58** (1998) 1804.

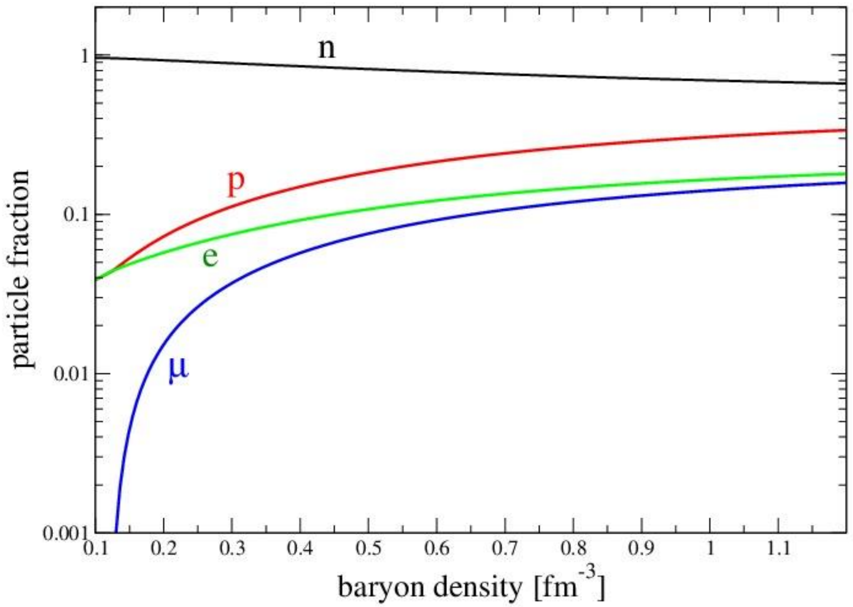
KVLBG :A. Kievsky, M. Viviani, D. Logoteta, I. Bombaci and L. Girlanda, Phys. Rev. Lett. **121** (2018) 072701.

Symmetry energy

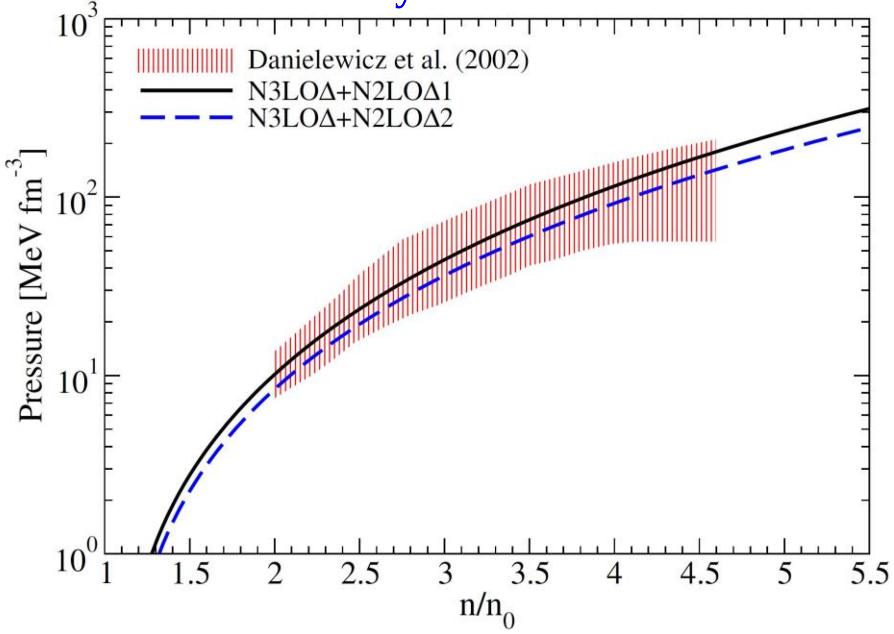


IAS = constraint from Isobaric Analog States in nuclei
(P. Danielewicz, J. Lee, Nucl. Phys. A922 (2014) 1)
Δr_{np} = neutron skin thickness of heavy nuclei
(X. Roca-Maza et al., Phys. Rev. C 87 (2013) 034301)

Particle fractions



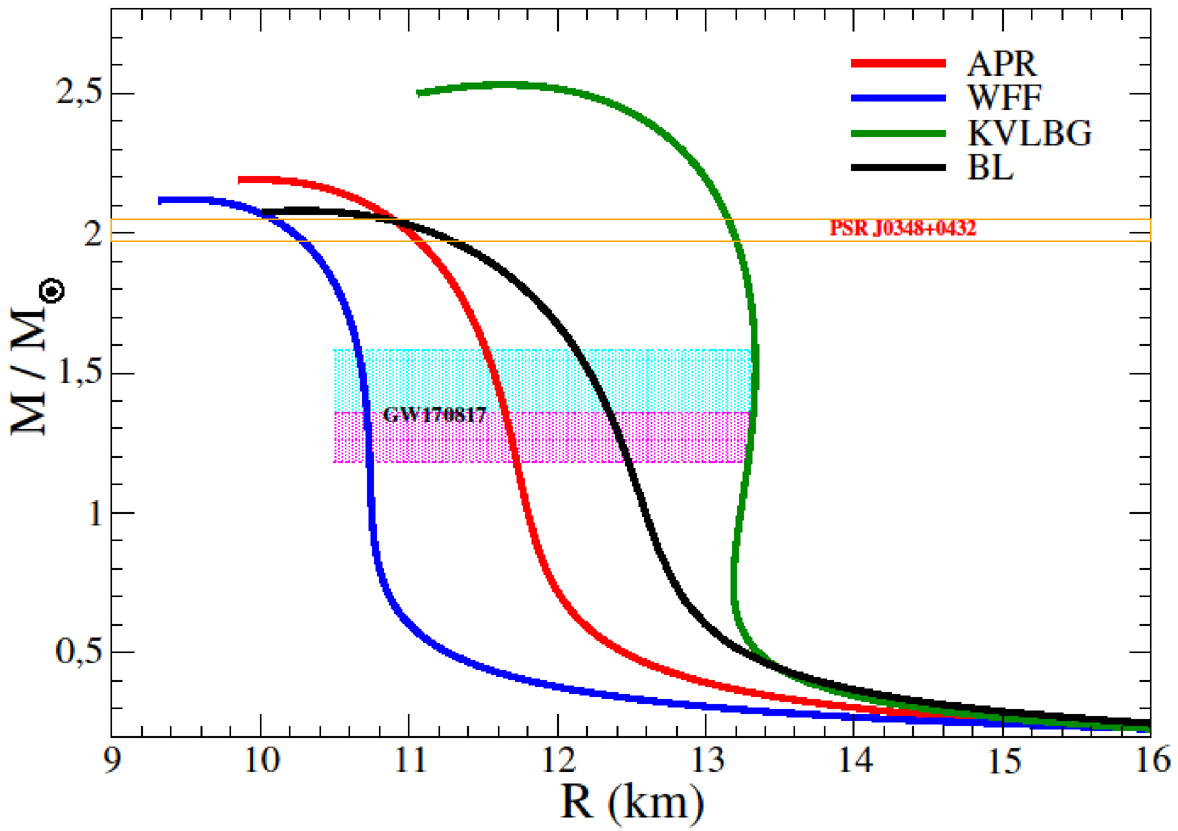
Pressure in symmetric NM



The red hatched area represents the region in the pressure–density plane for **SNM** which is consistent with the measured **elliptic flow of matter in collision experiments between heavy atomic nuclei** (Danielewicz et al. 2002).

I. Bombaci, D. Logoteta, Astron. and Astrophys. 609 (2018) A128

NS mass-radius relation



GW170817 data from: **B. P. Abbot et al. (LIGO-Virgo collaboration), Phys. Rev. Lett. 119 (2017) 161101**

$R_1 = (11.9 \pm 1.4)$ km and **$R_2 = (11.9 \pm 1.4)$ km** for the radius of the two neutron stars and **$1.36 \le M_1 / M_\odot \le 1.58$** and **$1.18 \le M_2 / M_\odot \le 1.36$** for their masses at the 90% credible level, for the case of "low-spin" prior.

Neutron stars: the maximum mass configuration

EOS	n_c (fm^{-3})	n_c / n_0	ρ_c (10^{14} g/cm ^{3})	M ($M_\odot$)	R (km)
BL	1.156	7.23	27.37	2.08	10.28
KVLBG	0.845	5.28	20.25	2.53	11.65
WFF	1.247	7.79	30.12	2.12	9.50
APR	1.146	7.16	27.87	2.19	9.97

I. Bombaci, D. Logoteta, Astron. and Astrophys. 609 (2018) A128

A. Kievsky, M. Viviani, D. Logoteta, I. Bombaci and L. Girlanda, Phys. Rev. Lett. **121** (2018) 072701

R.B. Wiringa, V. Ficks and A. Fabrocini, Phys. Rev. C **38** (1988) 1010.

A. Akmal, V.R. Pandharipande and D.G. Ravenhall, Phys. Rev. C 58 (1998) 1804.

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 $M_{max} = 0.71\ \mathbf{M}_{\odot}$ **(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 $\mathbf{M_{max} > 2\ M_{\odot}}$

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, PSR J0348+0432 and PSR J0740+6620

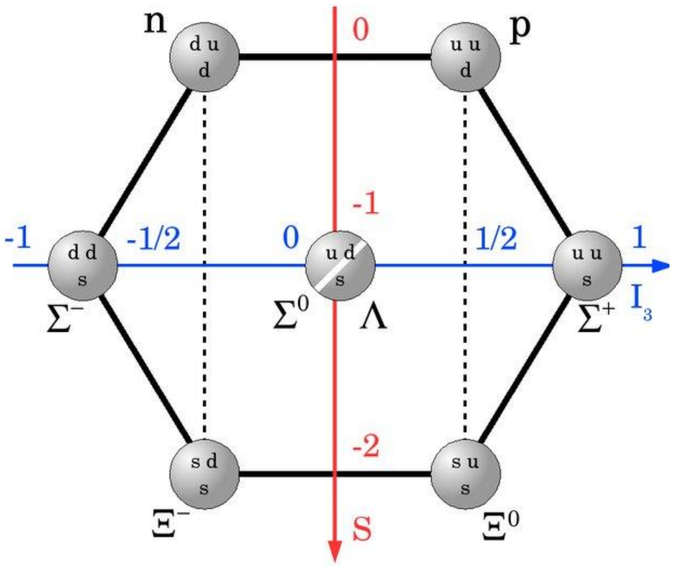
$$M_{NS} \approx 2\,M_{\odot}$$

Happy?

Not the end of the story!

Hyperons in dense matter and Hyperon Stars

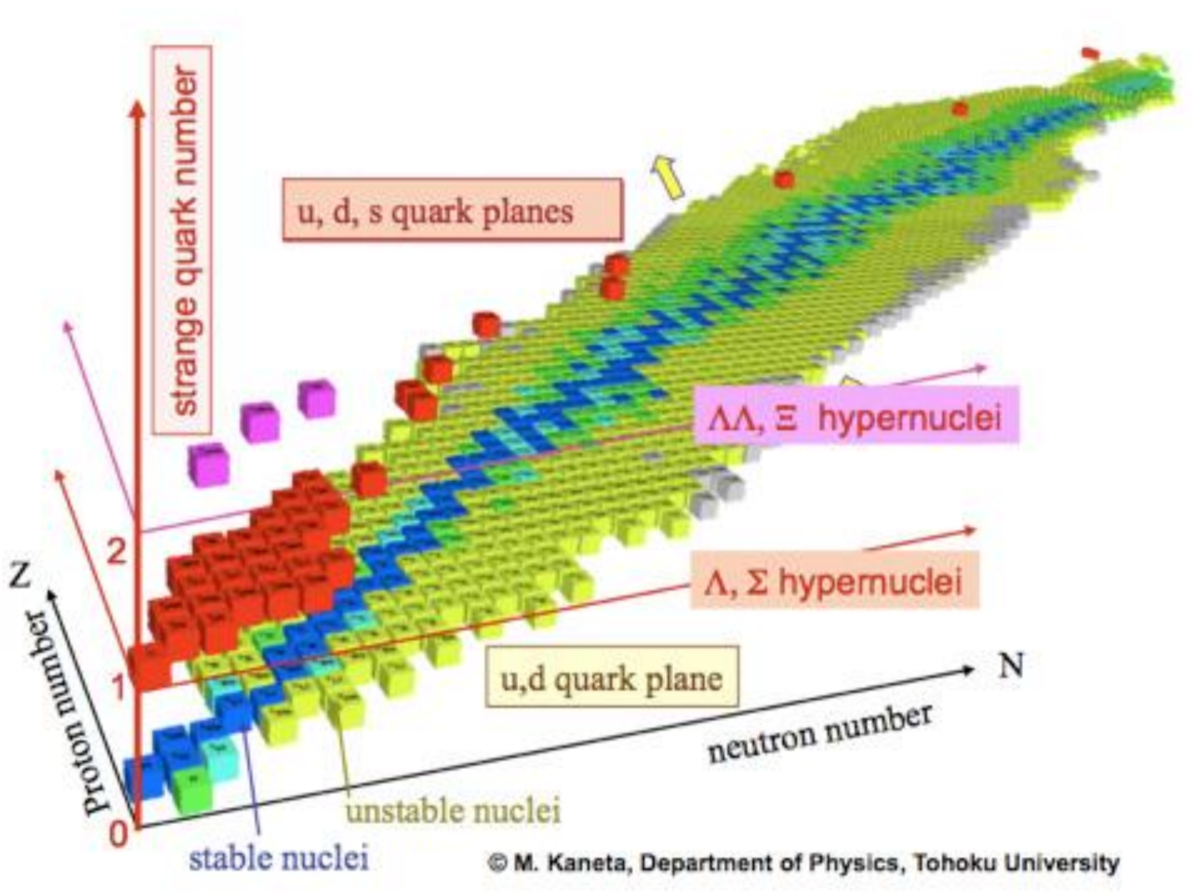
The **baryon octet : J$^\pi$ = (1/2)$^+$**



baryon name	Isospin	I_3	S	quarks	mass (MeV/c^2)	mean life
n	1/2	-1/2	0	udd	939.56	880 s
p	1/2	+1/2	0	uud	938.27	stable
Λ	0	0	-1	uds	1115.68	2.63×10^{-10} s
Σ^-	1	-1	-1	dds	1197.43	1.48×10^{-10} s
Σ^0	1	0	-1	uds	1192.55	7.4×10^{-20} s†
Σ^+	1	+1	-1	uus	1189.37	0.80×10^{-10} s
Ξ^-	1/2	-1/2	-2	dss	1321.32	1.64×10^{-10} s
Ξ^0	1/2	+1/2	-2	uss	1314.90	2.90×10^{-10} s

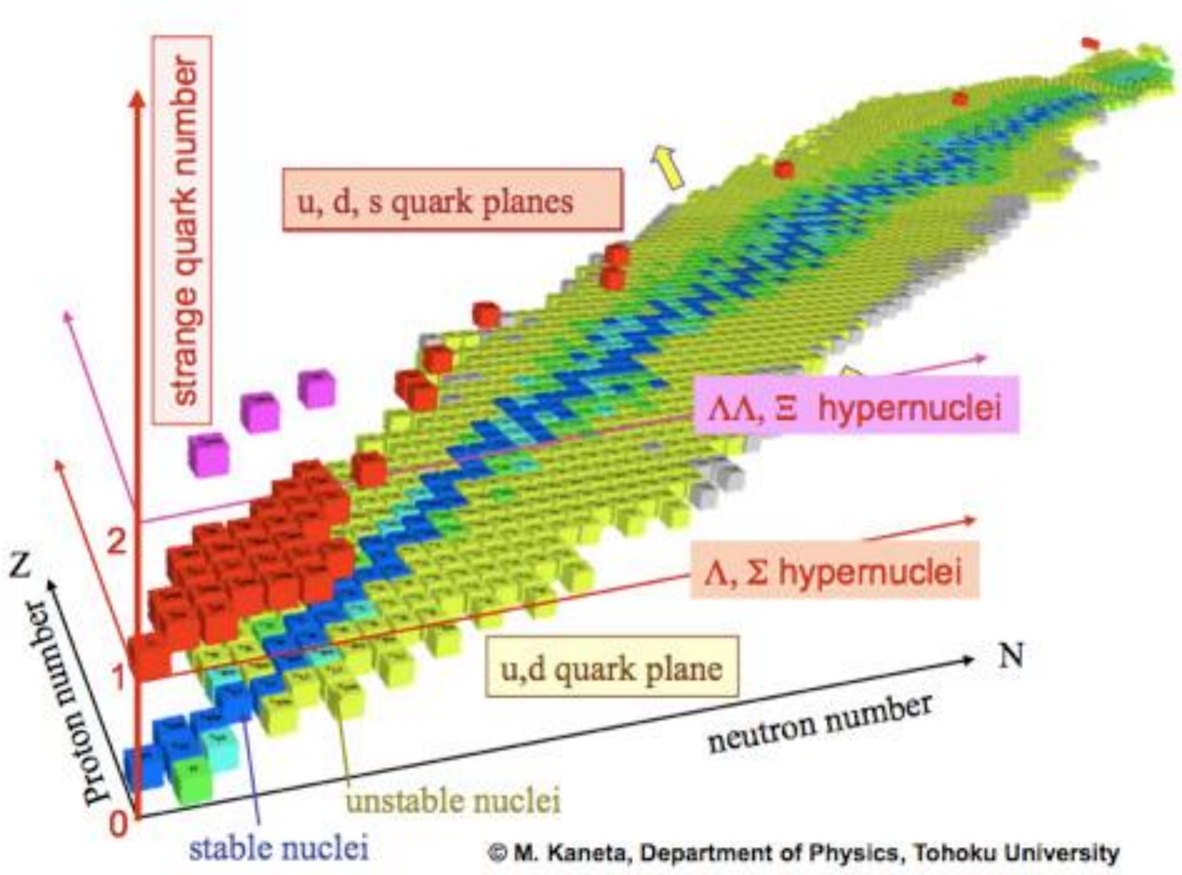
† The Σ^0 decays via the electromagnetic process $\Sigma^0 \rightarrow \Lambda + \gamma$ followed by the weak decay of the Λ.

Hypernuclei: (n, p, Y) bound states



valuable informations on the interactions between nucleons and hyperons

Hypernuclei: (n, p, Y) bound states



valuable informations on the interactions between nucleons and hyperons

Hyperons formation in dense nuclear matter

$$p + e^- \rightarrow \Lambda + \nu_e$$

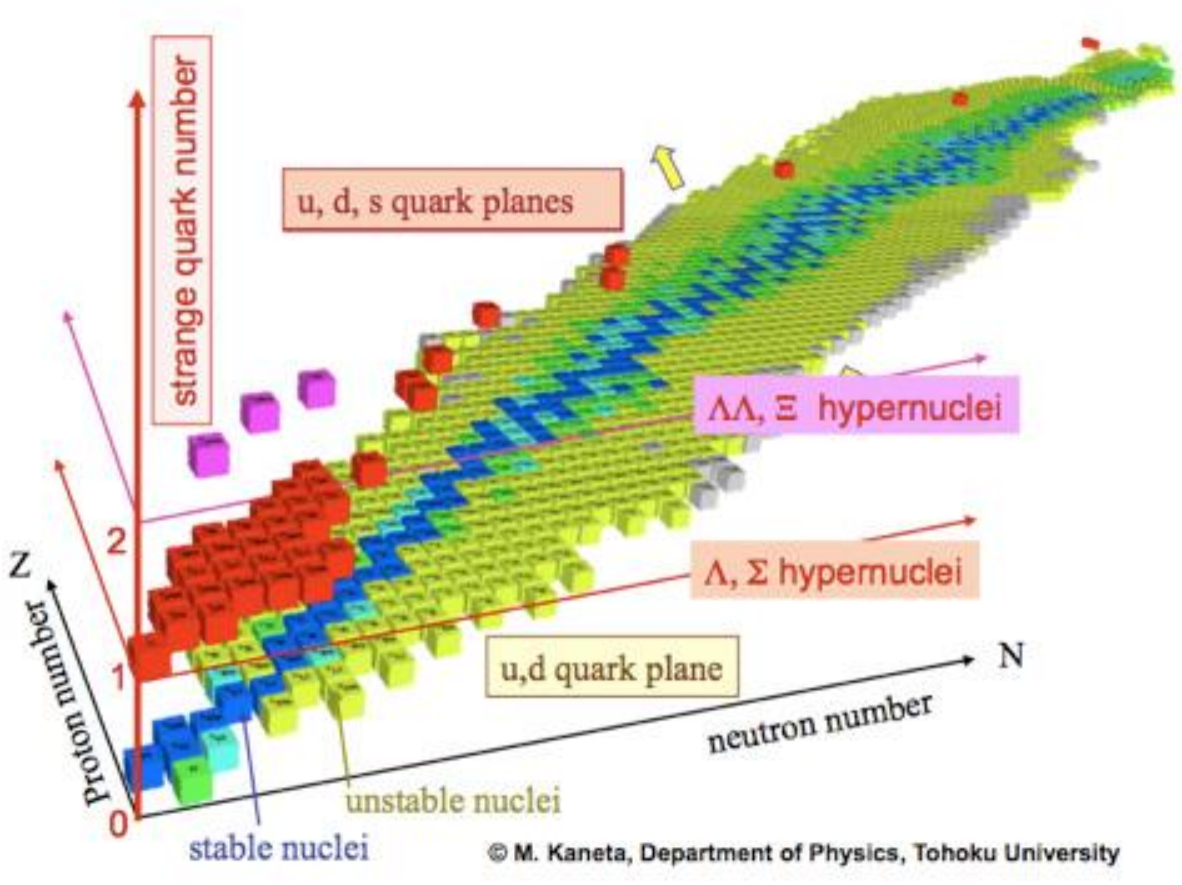
$$n + e^- \rightarrow \Sigma^- + \nu_e$$

$$\mu_\Lambda = \mu_p + \mu_e = \mu_n$$

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

(neutrino-free matter)

Hypernuclei: **(n, p, Y) bound states**



valuable informations on the interactions between nucleons and hyperons

Hyperons formation in dense nuclear matter

$$p + e^- \rightarrow \Lambda + \nu_e$$
$$n + e^- \rightarrow \Sigma^- + \nu_e$$

etc.

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

(neutrino-free matter)

At sufficiently high density nuclear matter turns into hyperonic matter

Hyperons threshold densities

(1) a simple extimate: **{n,p,e⁻} ideal gas in β-equilibrium** (**no strong interaction**) [non-rel. (n, p), ultrarel. e⁻]

$$\mu_n = \mu_p + \mu_e = m_\Lambda c^2 \longrightarrow n^{*\Lambda} = 0.86\, fm^{-3} = 5.4\, n_0$$

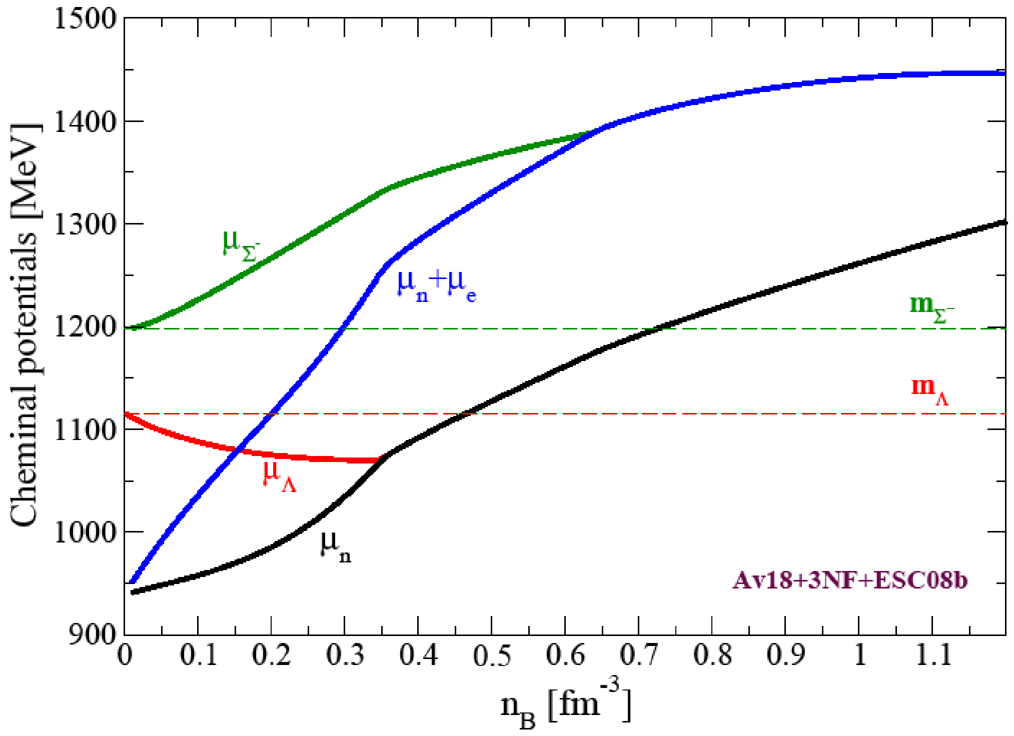
(2) Effect of the **strong interaction**

NN(Av18) + NNN + NY(ESC08b)
(no hyperonic TBF)

$$n^{*\Lambda} = 0.35\, fm^{-3} = 2.19\, n_0$$

$$n^{*\Sigma^-} = 0.64\, fm^{-3} = 4\, n_0$$

$$n^{*\Lambda}, n^{*\Sigma^-} < n_c(M_{max})$$



I. Bombaci, D. Logoteta, EPJ Web of Conference 117 (2016) 07005

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EOS	n_c (fm^{-3})	n_c / n_0	ρ_c (10^{14} g/cm ^{3})	M ($M_\odot$)	R (km)
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KVLBG	0.845	5.28	20.25	2.53	11.65
WFF	1.247	7.79	30.12	2.12	9.50
APR	1.146	7.16	27.87	2.19	9.97

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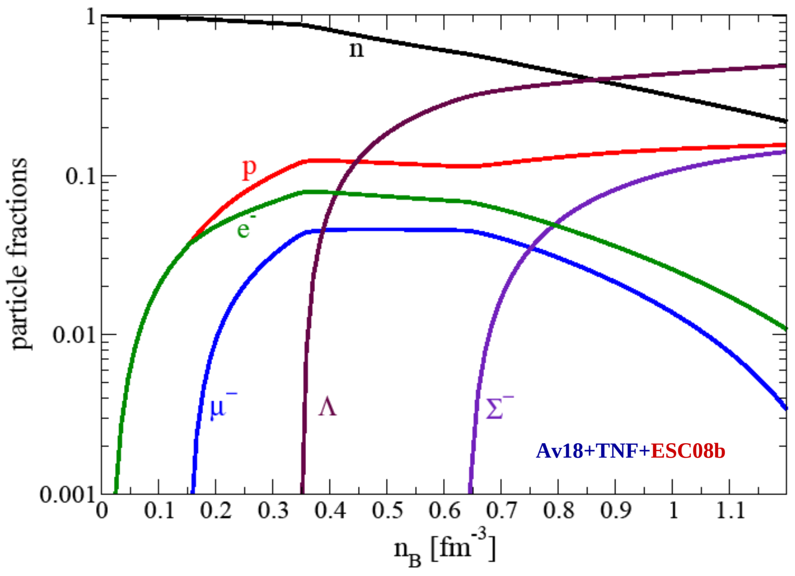
Particle fractions

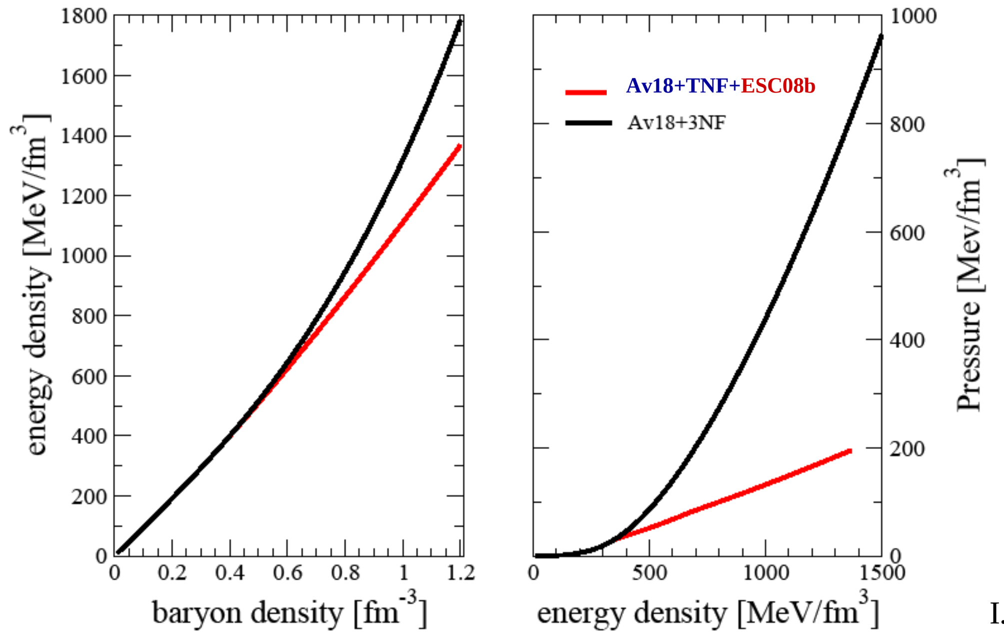


NN(Av18) + NNN + NY(ESC08b)

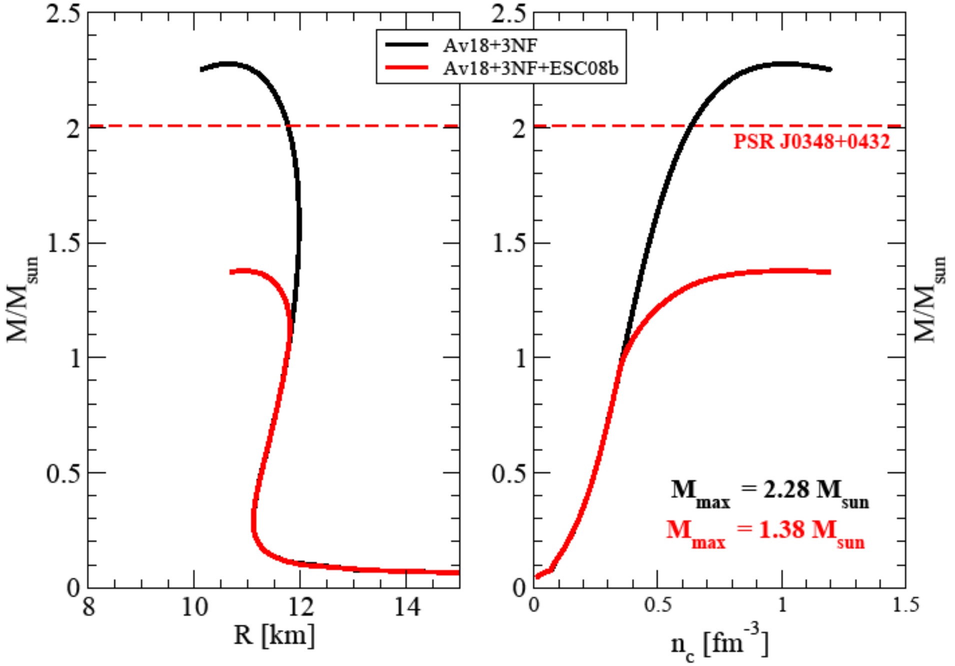
no hyperonic TBF

hyperons produce a strong softening of the EOS

Equation of State of Hyperonic Matter



Stellar mass

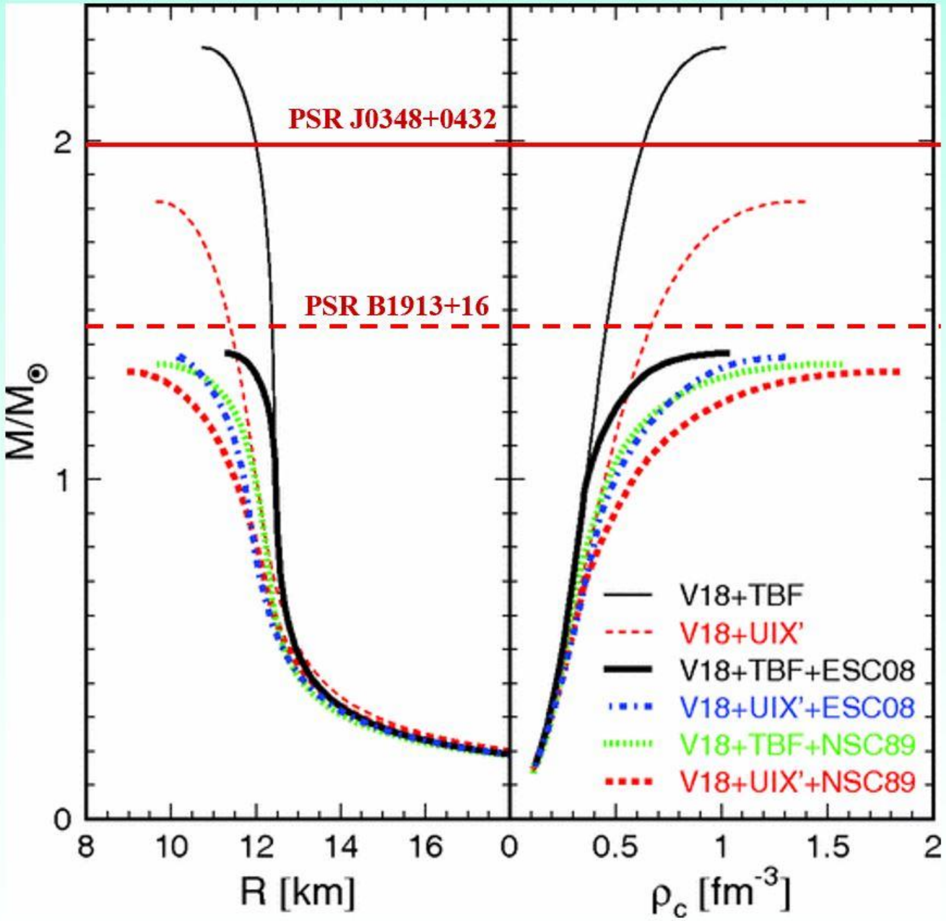


I. Bombaci, D. Logoteta, EPJ Web of Conference 117 (2016) 07005

Effect of the YY interaction

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

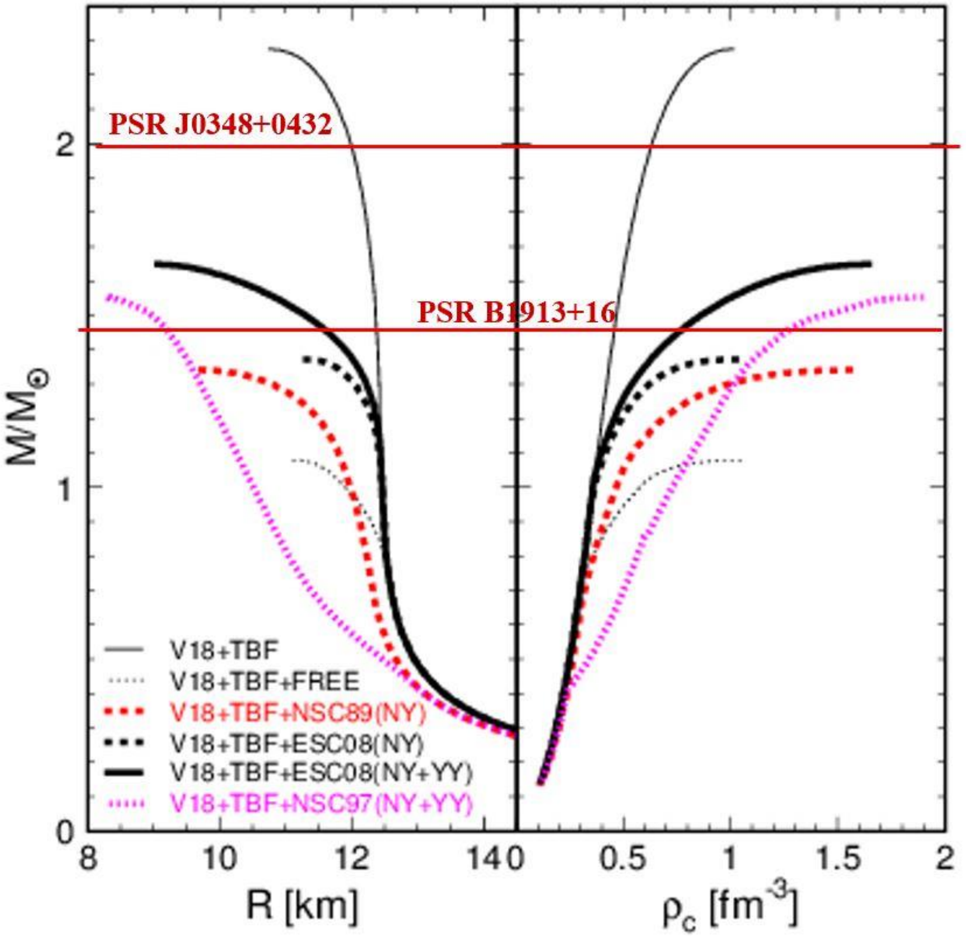
no YY int.   no hyperonic TBF



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

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

no hyperonic TBF



T. Rijken, H.-J. Schulze, Eur. Phys. J. A 52 (2016) 21

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 problem which likely originates from our incomplete knowledge of the baryonic interactions.

Hyperonic three-body interactions as a possible solution of the hyperon puzzle

As mentioned before, **three-nucleon interactins** are a necessary ingredient for an accurate description of nuclei and nuclear matter within non-relativistic approaches.

Thus, it is rather obvious to suppose the existence of **hyperonic three-body interactions** (of the type **NNY, NYY, YYY**).

The **NNΛ interaction** was in fact first hypothesized at the end of the 1950s (*), *i.e.* during the early days of hypernuclear physics, as an important ingredient to calculate the **binding energy of hypernuclei**.

It is thus reasonable to expect that **hyperonic three-body interactions** can influence dense-matter EoS and represent a **likely candidate to solve the hyperon puzzle**.

(*)

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, Academy of Sciences, USSR, Vol I (1960) 587.

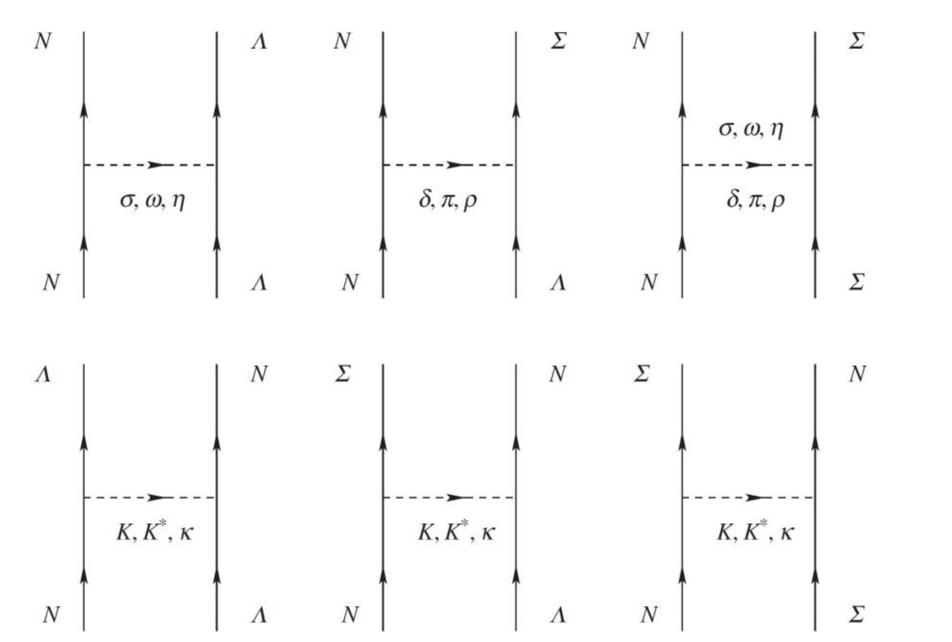
Microscopic approach to hyperonic matter EOS

input

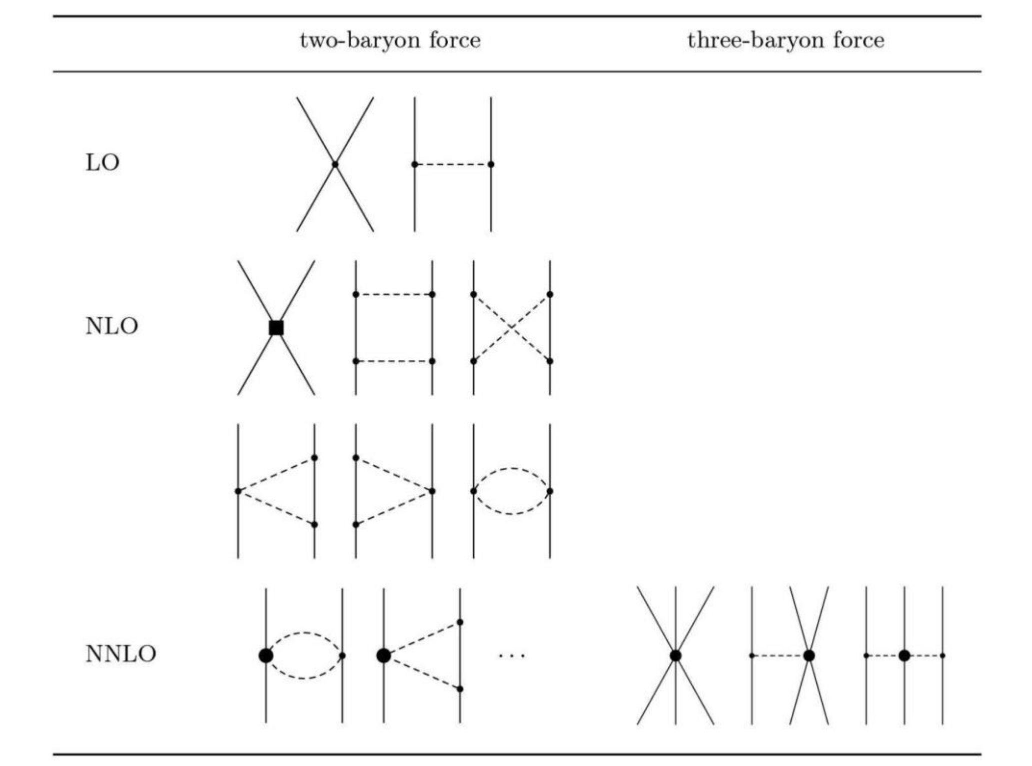
2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)
3BF: NNN, NNY, NYY, YYY, 4BF: …….

Phenomenological meson-exchange models:

(Jülich, Nijmegen)



Chiral Effective Field Theory (ChEFT)



Microscopic approach to hyperonic matter EOS

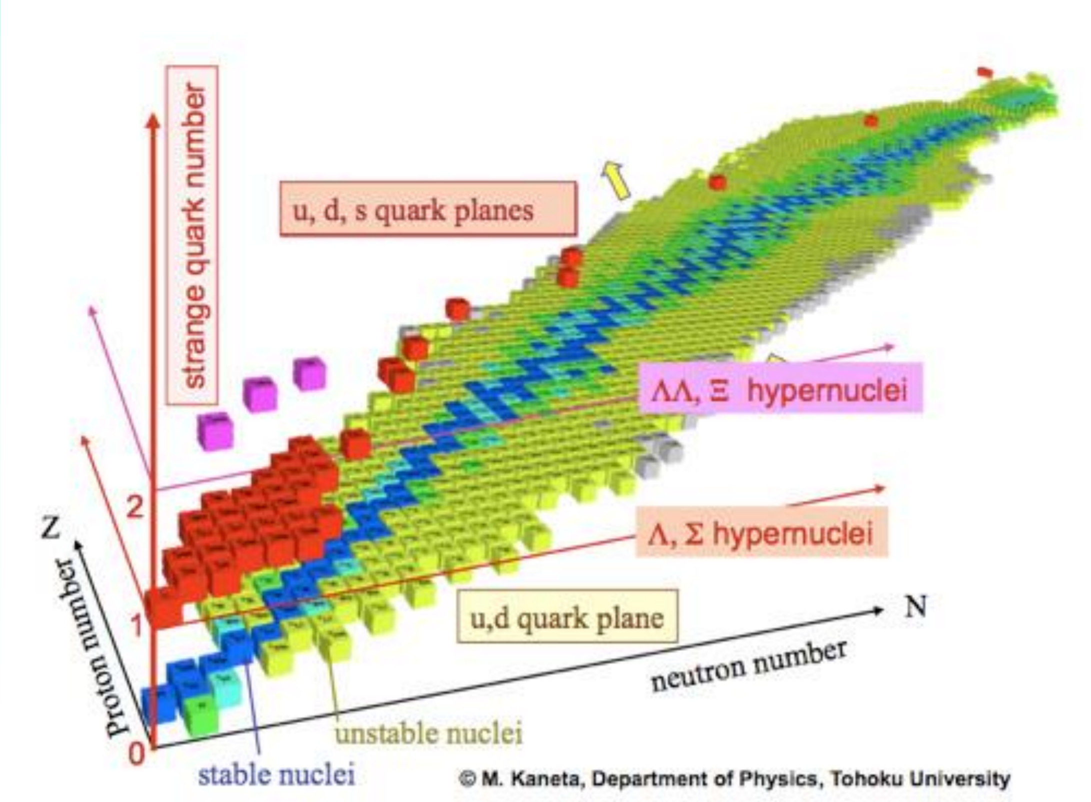
input

2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)
3BF: NNN, NNY, NYY, YYY, 4BF: …….

Hyperonic sector: experimental data

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

2. **Hypernuclei : ≈ 40 $_{\Lambda}$X , ≈ 5 $_{\Lambda\Lambda}$X**
   a few Ξ^-–hypernuclei
   (nuclei ≈ 3300)



E. Botta, T. Bressani, G. Garbarino, Eur. Phys. J. A 48 (2012) 41
C. Curceanu, *et al.*, Rev. Mod. Phys. 91 (2019) 025006
O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. 57, (2006) 564.
L. Tolos, and L. Fabbietti, Prog. Part. Nucl. Phys. 112 (2020) 103770

A breakthrough for determining the NY and YY interactions

Recently, the **ALICE Collaboration** has demonstrated that **NY** and **YY interactions** can be investigated with high precision using ***p*–*p* and *p*–Pb collisions at the LHC** (using the technique called **femtoscopy**).

ALICE Collaboration. *p*–*p*, *p*–Λ and Λ–Λ correlations studied via femtoscopy in *pp* reactions at $\sqrt{s}$ = 7 TeV. *Phys. Rev. C* 99, 024001 (2019).
ALICE Collaboration. Scattering studies with low-energy kaon–proton femtoscopy in proton–proton collisions at the LHC. *Phys. Rev. Lett*. 124, 092301 (2020).
ALICE Collaboration. Study of the Λ–Λ interaction with femtoscopy correlations in *pp* and *p*–Pb collisions at the LHC. *Phys. Lett. B* 797, 134822 (2019).
ALICE Collaboration. First observation of an attractive interaction between a proton and a cascade baryon. *Phys. Rev. Lett*. 123, 112002 (2019).
ALICE Collaboration. Investigation of the *p*–Σ^0 interaction via femtoscopy in *pp* collisions. *Phys. Lett. B* 805, 135419 (2020).
ALICE Collaboration. Unveiling the strong interaction among hadrons at the LHC, Nature 588, 232(2020)

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^-, Σ^0, Σ^+, Ξ^-, Ξ^0)

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

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

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.

A simplified version for hyperonic matter: {n, p, Λ}-matter

(D. Logoteta, I. Vidaña, I. Bombaci, Eur. Phys. J. A 55 (2019) 207)

Interactions:

NN ChEFT N3LO $\Delta(1232)$ Piarulli et al., Phys. Rev. C 94 (2016) 054007

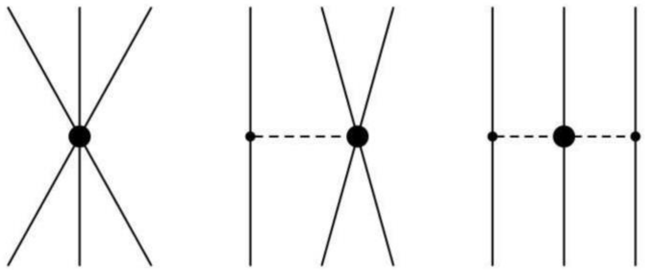
NNN ChEFT N2LO $\Delta(1232)$ Epelbaum et al., Phys. Rev C 66 (2002) 064001
Navratil, Few-Body Syst. 41 (2007) 117

average $\rightarrow$ $V^{eff}_{NN}(n)$ Logoteta et al., Phys. Rev. C 94 (2016) 064001

NΛ Nijmegen Soft Core 97 (NSC97a,e) Rijken et al., Phys. Rev. C 59, (1999) 21;
Stocks , Rijken, Phys. Rev. C 59 (1999) 3009

NNΛ ChEFT N2LO Petschauer et al., Phys. Rev. C 93 (2016) 014001

average $\rightarrow$ $V^{eff}_{N\Lambda}(n)$ Petschauer et al., Nucl. Phys. A 957 (2017) 347



Saturation by decuplet baryons $\longrightarrow$

Only one **LEC (H')** is left

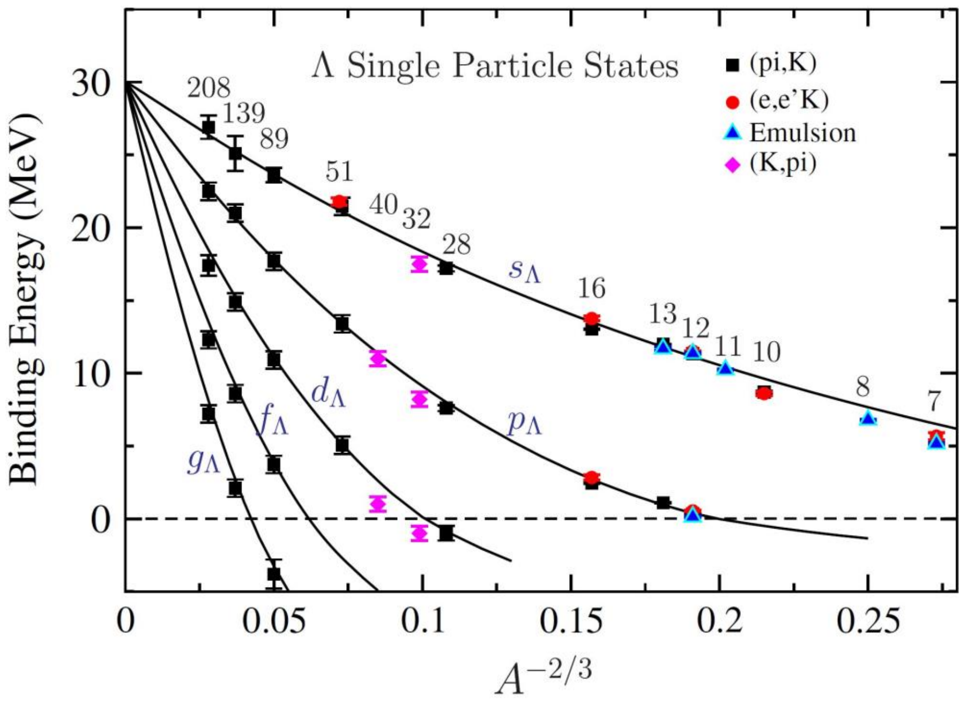
$$\boxed{H' = \frac{\beta}{f_\pi^2}}$$

$f_\pi = 93$ MeV   pion decay constant

We fix **β** to to have, in **symmetric nuclear matter** at the empirical saturation density $\mathbf{n_0 = 0.16\ fm^{-3}}$ **:**

$$U_\Lambda(k = 0, n_0) = B_\Lambda^\infty$$

where B_Λ^∞ is the extrapolation to infinite nuclear matter of the **binding energy** B_Λ of **Λ in hypernuclei**



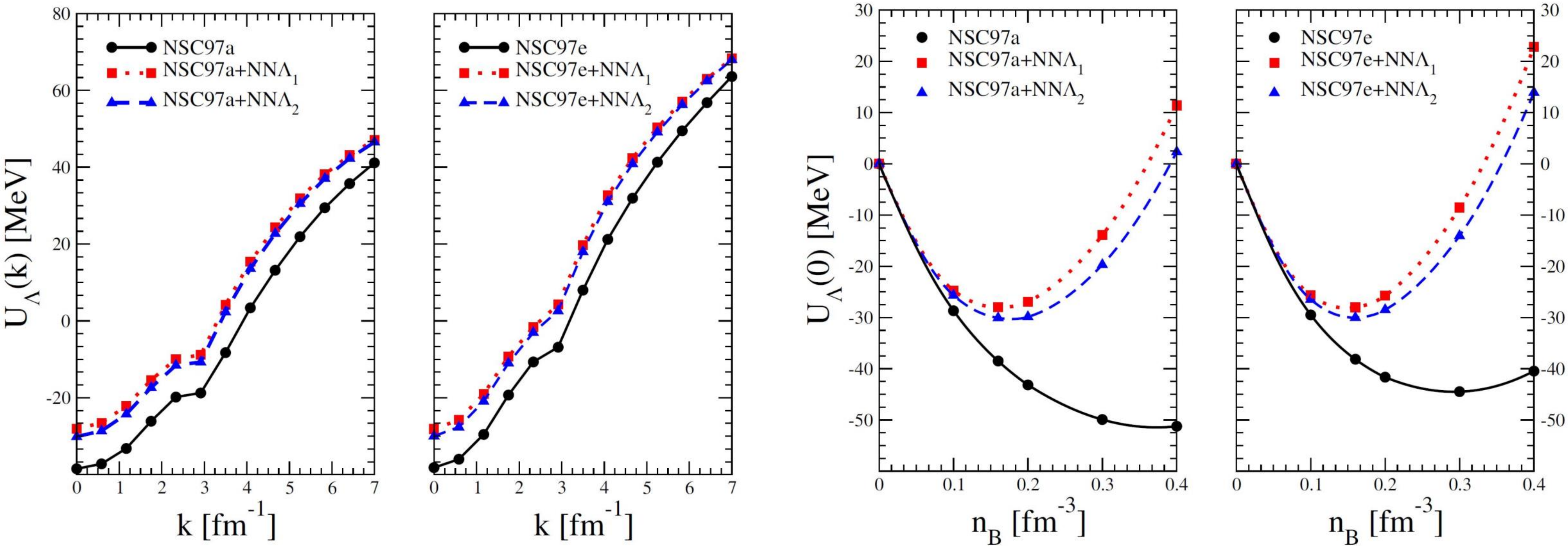
$$U_\Lambda(k = 0, n_0) = -28\ \mathbf{MeV} \qquad (\mathrm{NN\Lambda_1})$$

$$U_\Lambda(k = 0, n_0) = -30\ \mathbf{MeV} \qquad (\mathrm{NN\Lambda_2})$$

D. Logoteta, I. Vidaña, I. Bombaci, Eur. Phys. J. A 55 (2019) 207

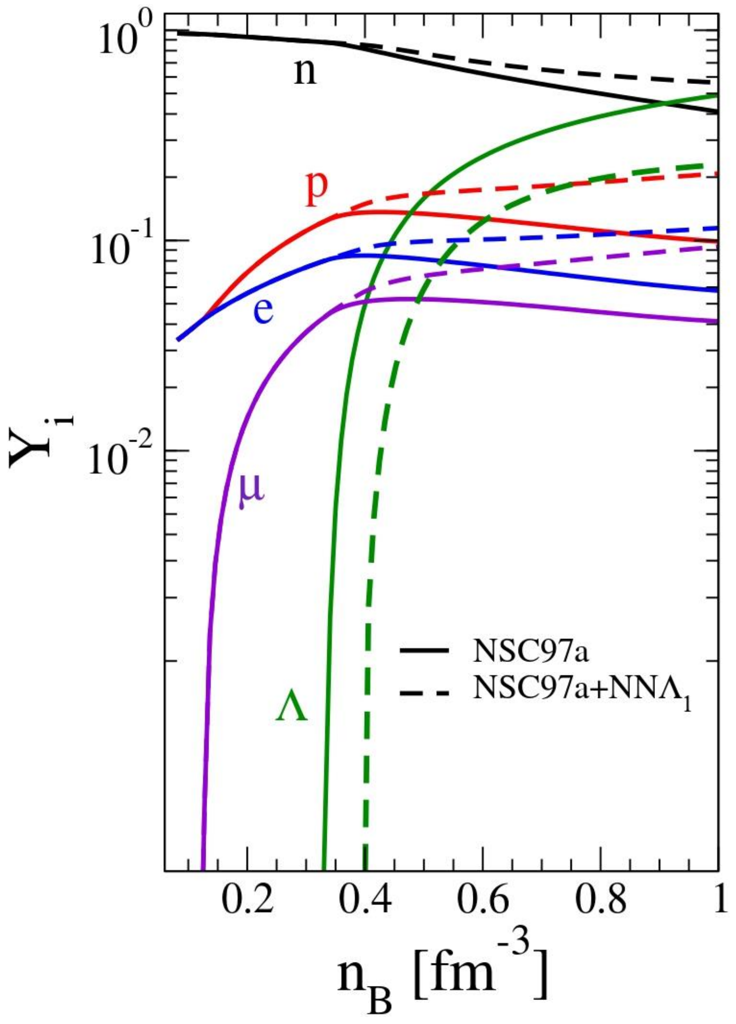
Single particle potential of **Λ in Symmetric Nuclear Matter**

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

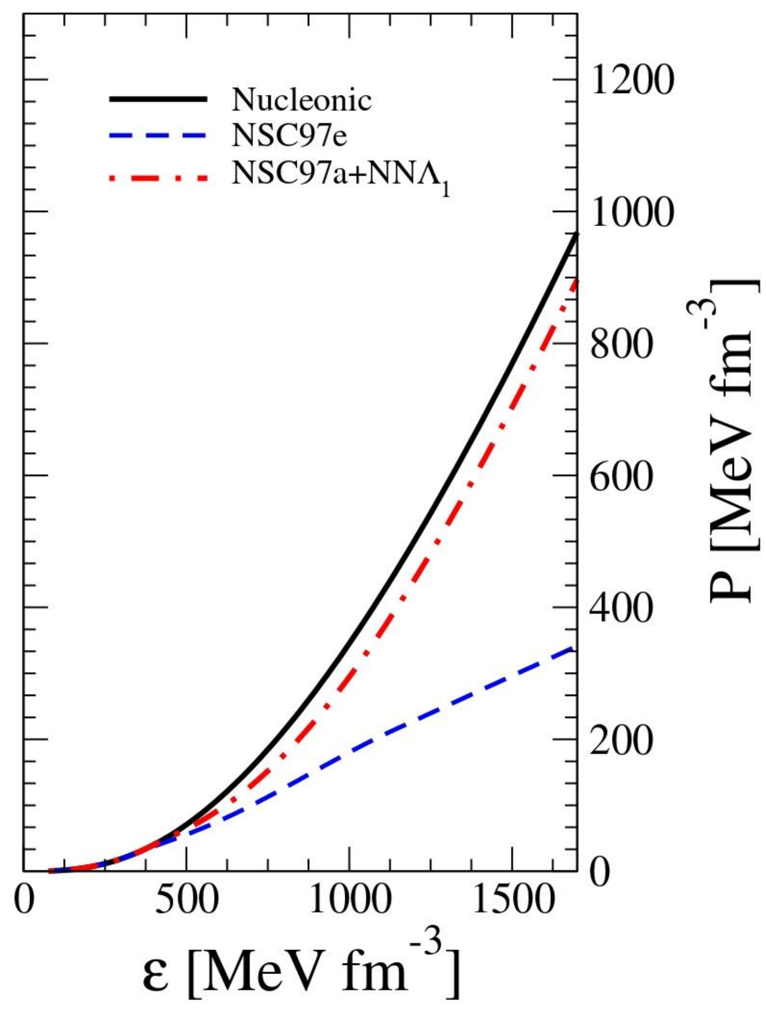


D. Logoteta, I. Vidaña, I. Bombaci, Eur. Phys. J. A 55 (2019) 207

Particle fractions in
β–stable (n, p, Λ) matter

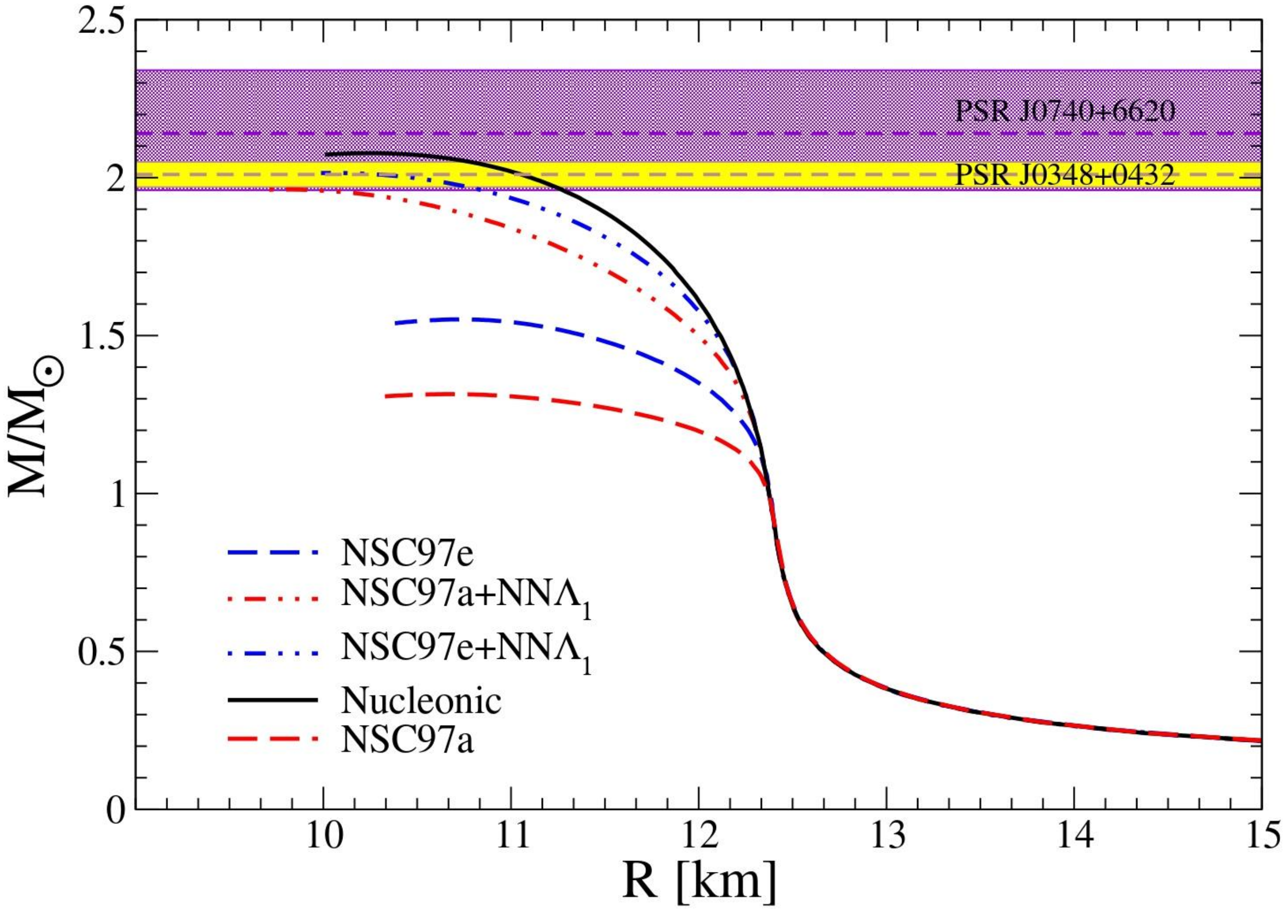


EOS



D. Logoteta, I. Vidaña, I. Bombaci, Eur. Phys. J. A 55 (2019) 207

Mass–Radius relation

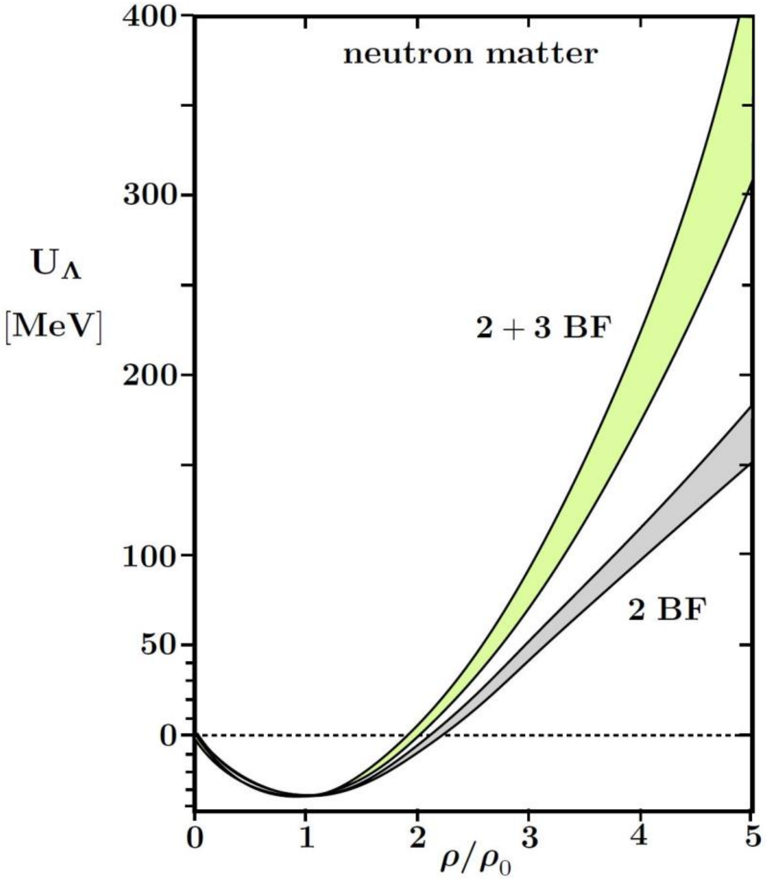


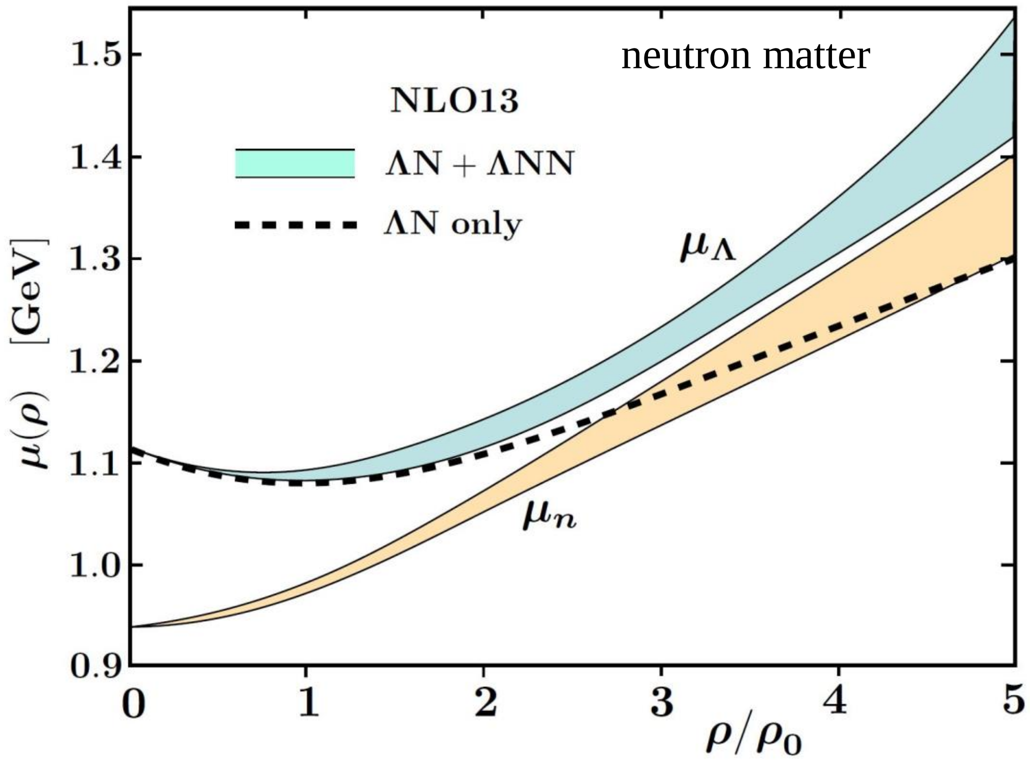
Properties of the maximum mass configuration

	$M_{max}(M_\odot)$	R (km)	n_c (fm^{-3})
Nucleonic	2.08	10.26	1.15
NSC97a	1.31	10.60	1.40
NSC97a+NNΛ_1	1.96	9.80	1.30
NSC97a+NNΛ_2	1.97	9.87	1.28
NSC97e	1.54	10.81	1.18
NSC97e+NNΛ_1	2.01	10.10	1.20
NSC97e+NNΛ_2	2.02	10.15	1.19

Hyperonic three-body interactions could represent a likely solution of the hyperon puzzle in Neutron Stars

D. Logoteta, I. Vidaña, I. Bombaci, Eur. Phys. J. A 55 (2019) 207

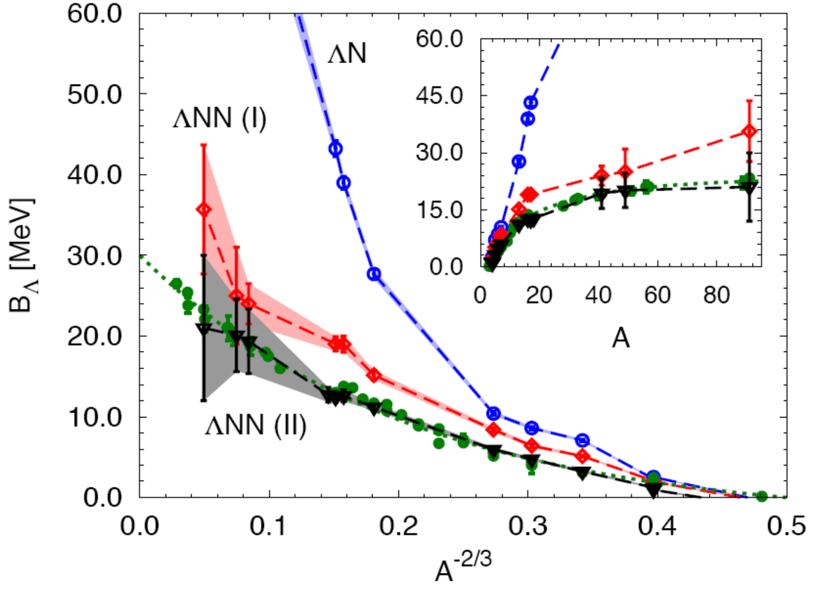


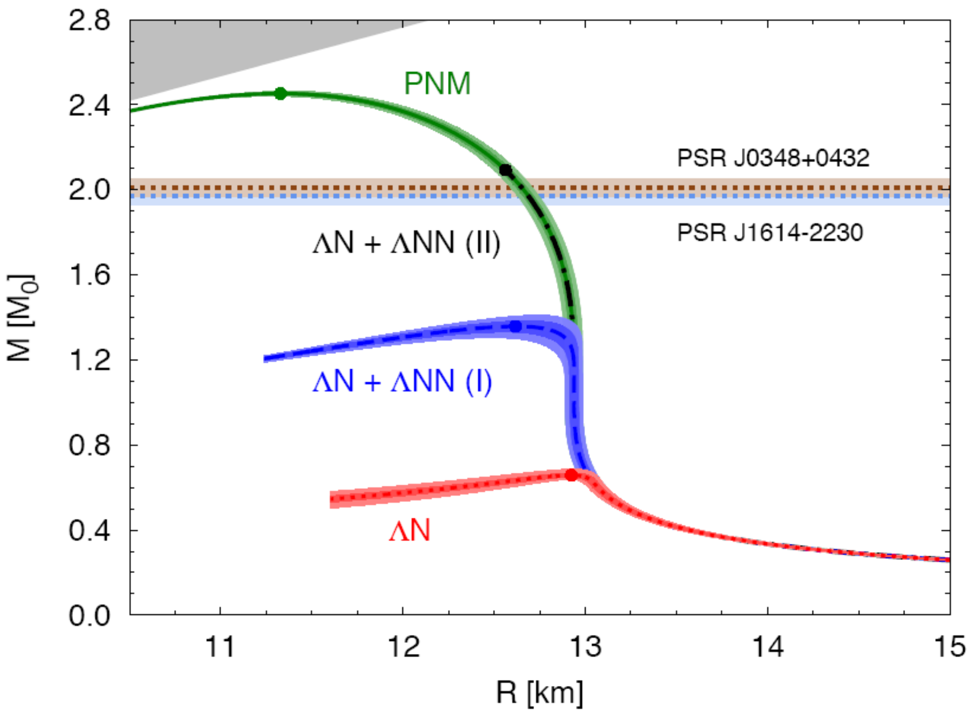


D. Gerstung, N. Kaiser, W. Weise, Eur. Phys. J. A 56 (2020) 175

«The combined repulsion from two- and three-body hyperon-nuclear interactions can indeed be potentially strong enough to avoid the appearanche of Λ hyperons in neutron stars»

Microscopic EOS for hyperonic matter: AFDM





(n , Λ) - matter

Av8’ + UXI + ΛNN

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

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

Within this model

“Hyperon Stars” do not contain hyperons

The hyperon puzzle in Neutron Stars

Hyperonic three-body interactions could represent a likely solution of the hyperon puzzle in Neutron Stars

but

if hyperonic three-body interactions are repulsive enough, hyperons will never appear at the densities encountered in neutron star cores.

In this case "hyperon stars" would not contain hyperons at all, that is, we will go back to the case of **nucleonic stars**.

This could be a physically acceptable conclusion if the "true" hyperonic three-body interactions make **hyperon formation non convenient from an energetic point of view**, **contrary to the simple expectation based on the ideal Fermi gas argument.**

Neutron Stars in the QCD phase diagram

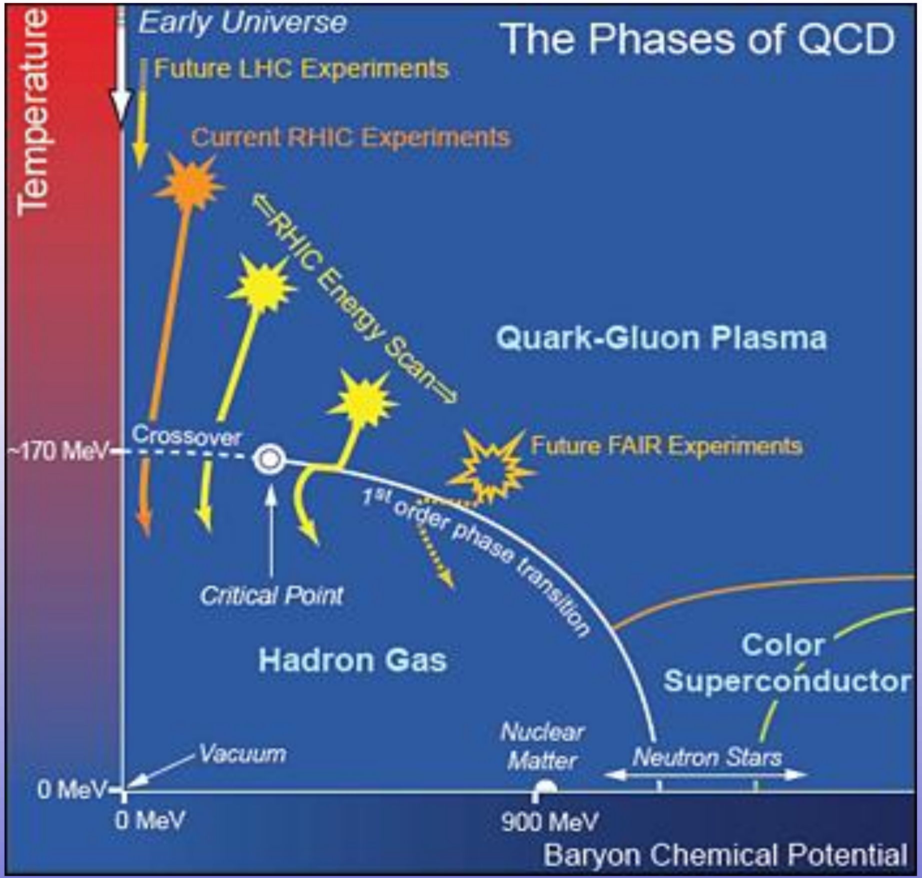
Lattice QCD
at μ_b=0 and finite T

- 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

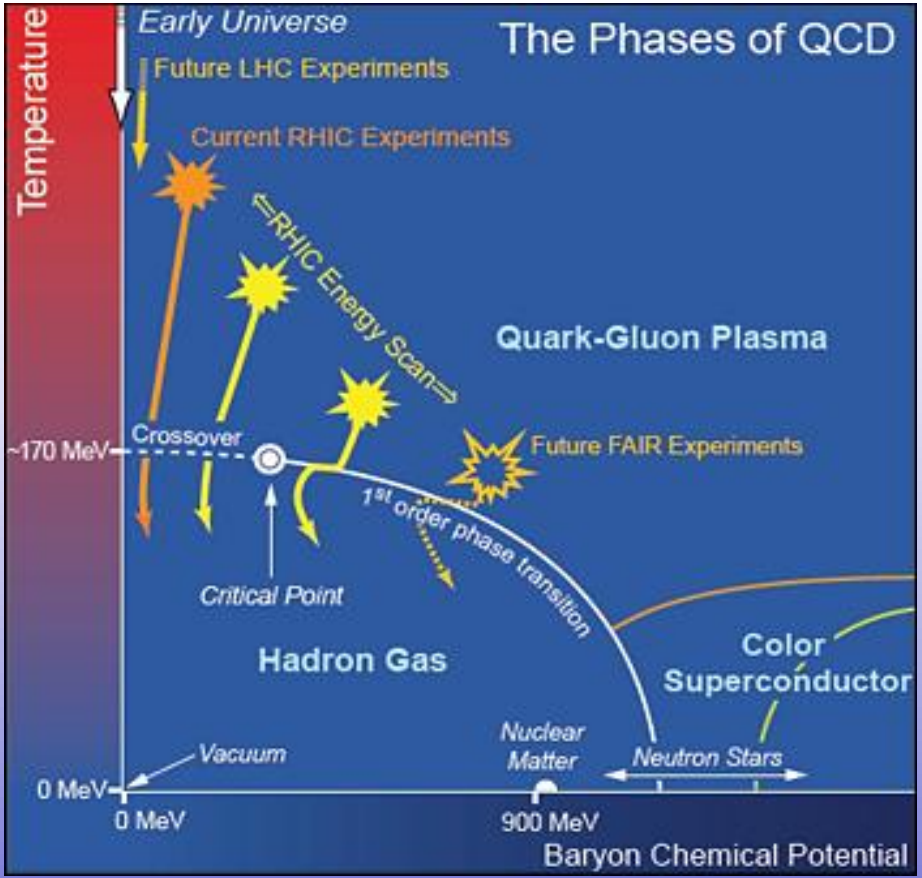
Quark deconfinement transition expected of the first order

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 in the QCD phase diagram

The core of the most massive Neutron Stars is one of the best candidates in the Universe where a quark-deconfined phase of matter (Quark Matter) can be found



Neutron Stars: high μ_b and low T

Lattice QCD calculations are presently not possible

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

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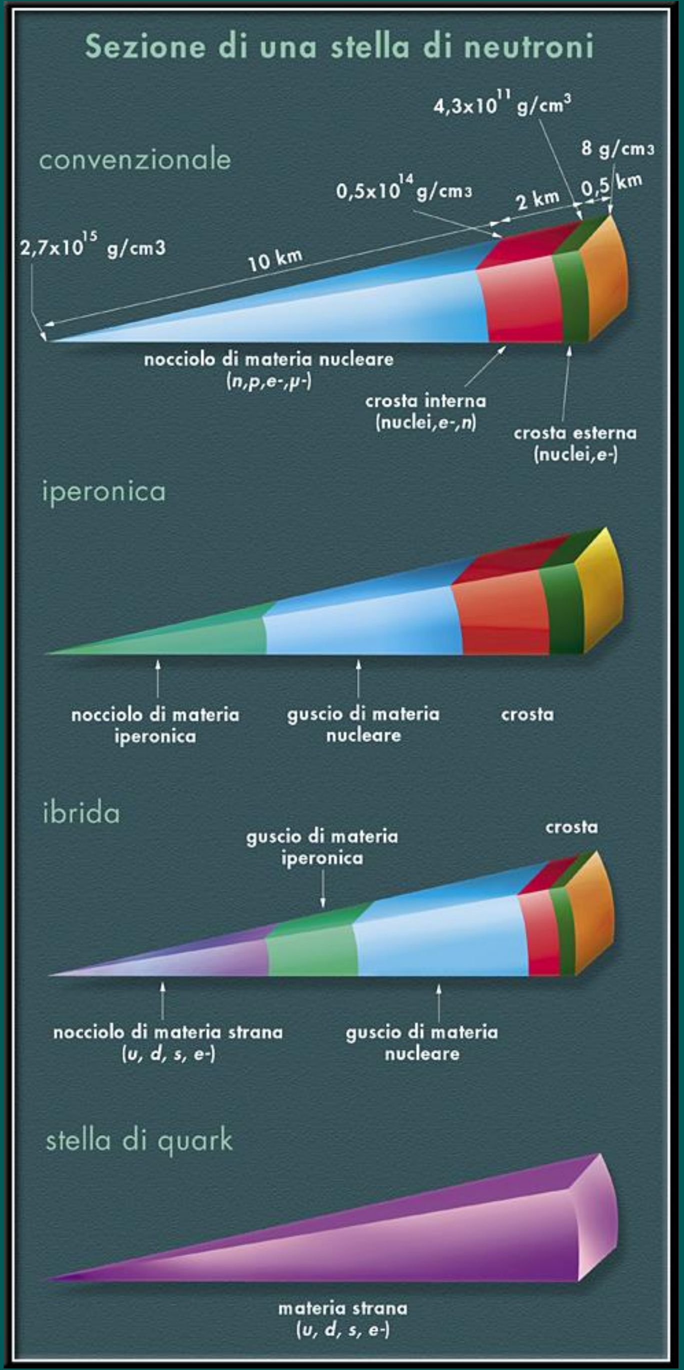


I. Bombaci, A. Drago, INFN Notizie, n. 13, 15 (2003)

"Neutron Stars"

Nucleon Stars

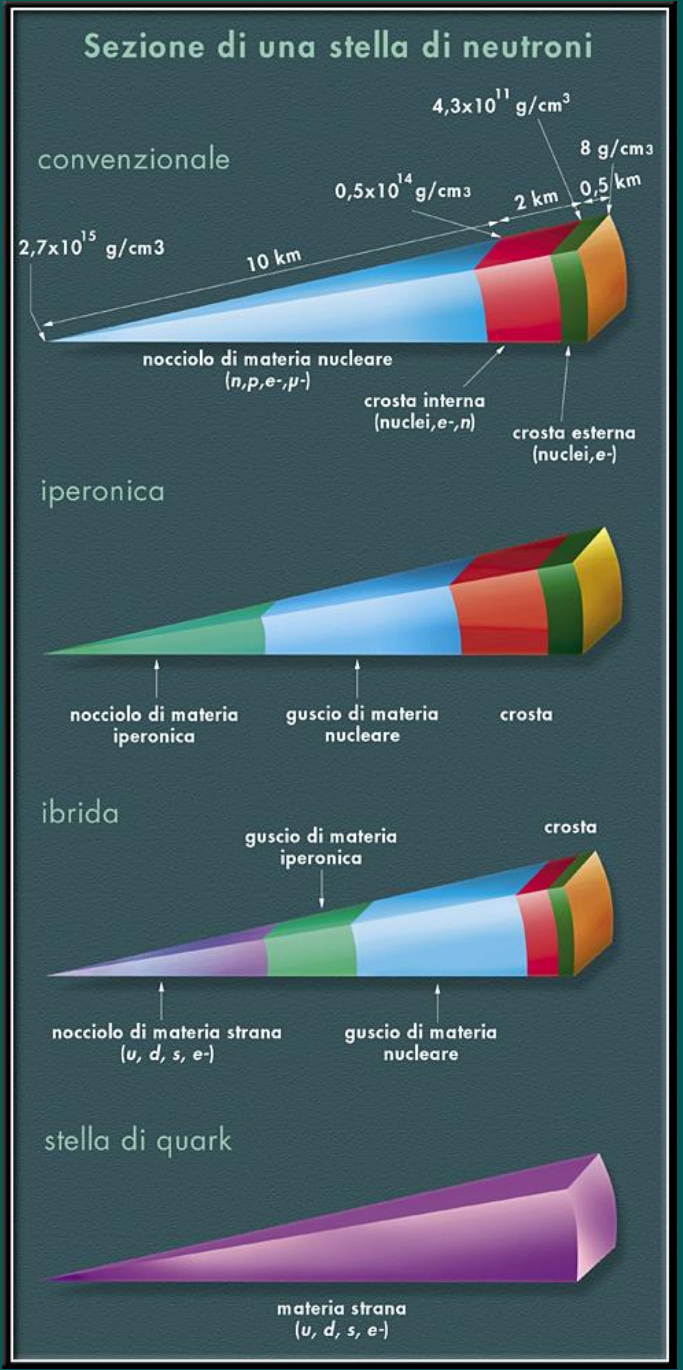
Hyperon Stars

$\Big\}$ **Hadronic Stars**

Hybrid Stars

Strange Stars

$\Big\}$ **Quark Stars**



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

"Neutron Stars"

Nucleon Stars

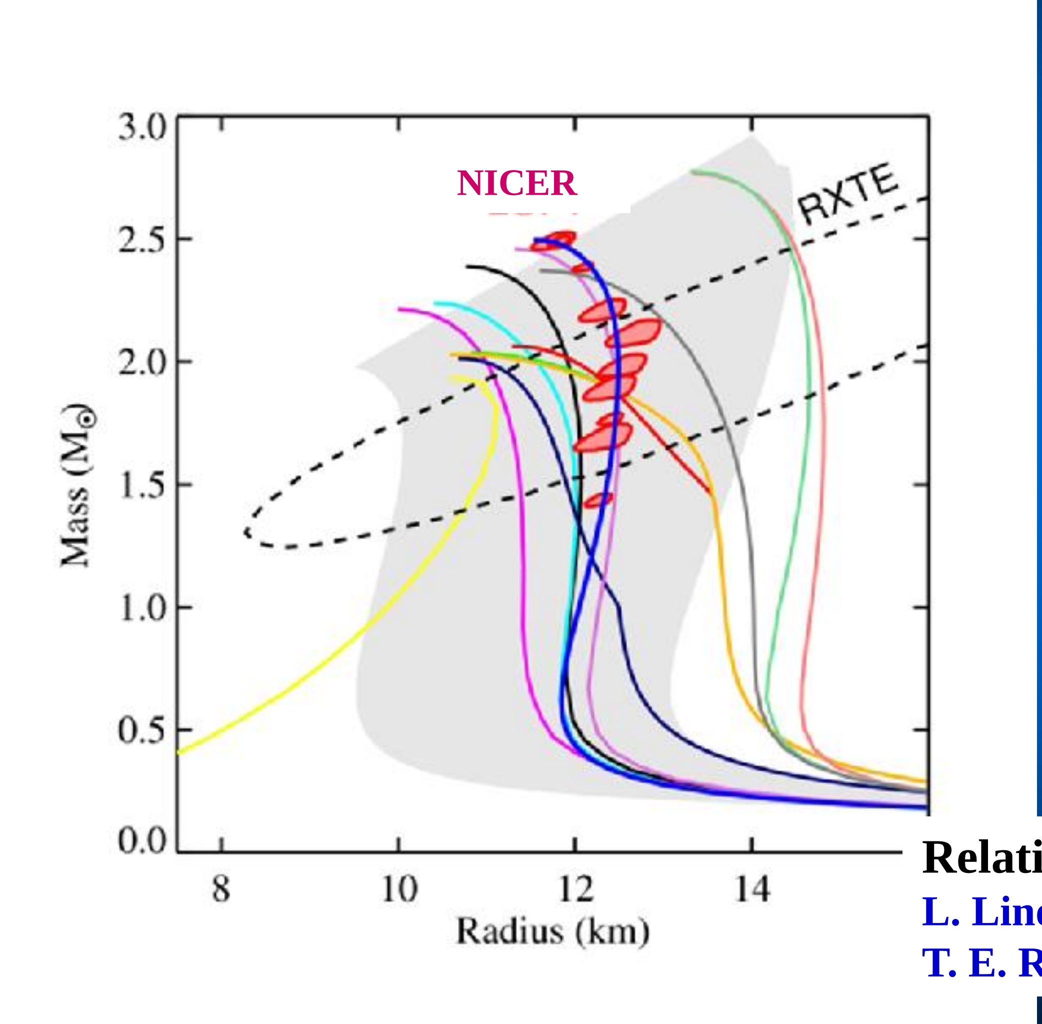
Hadronic Stars

What type(s) of Neutron Stars does Nature produce?

Quark Stars

Strange Stars

The current accepted paradigm:
one family of "Neutron Stars"



"Measuring" the EOS

accurate measurements of the mass and radius of several neutron stars

Determination of the cold (T=0) dense matter EOS

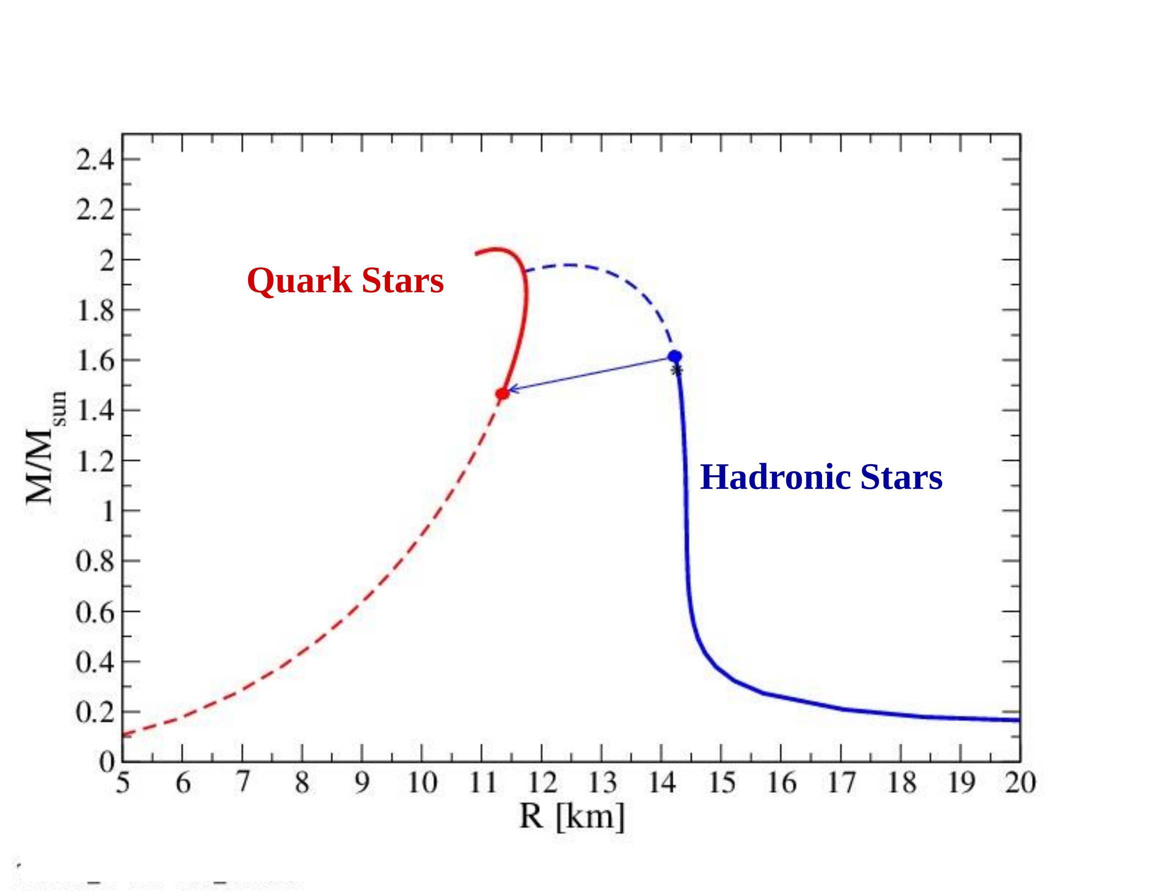
$$P = P(\rho)$$

Relativistic inverse stellar structure problem:

L. Lindblom, ApJ 398 (1992) 569

T. E. Riley et al., MNRAS 478 (2018) 1093

The new paradigm:
two families of “Neutron Stars”



The Astrophysical Journal, 586:1250–1253, 2003 April 1

ApJ 586 (2003)

GAMMA-RAY BURSTS FROM DELAYED COLLAPSE OF NEUTRON STARS TO QUARK MATTER STARS

Z. Berezhiani,[1] I. Bombaci,[2] A. Drago,[3] F. Frontera,[3,4] and A. Lavagno[5]
Received 2002 September 12; accepted 2002 December 2

ABSTRACT

We propose a model to explain how a gamma-ray burst can take place days or years after a supernova explosion. Our model is based on the conversion of a pure hadronic star (neutron star) into a star made at least in part of deconfined quark matter. The conversion process can be delayed if the surface tension at the

The Astrophysical Journal, 614:314–325, 2004 October 10

ApJ 614 (2004)

QUARK DECONFINEMENT AND IMPLICATIONS FOR THE RADIUS AND THE LIMITING MASS OF COMPACT STARS

Ignazio Bombaci,[1] Irene Parenti,[1] and Isaac Vidaña[1]
Received 2003 August 4; accepted 2004 June 22

ABSTRACT

We study the consequences of the hadron-quark deconfinement phase transition in stellar compact objects when finite-size effects between the deconfined quark phase and the hadronic phase are taken into account. We show that above a threshold value of the central pressure (gravitational mass) a neutron star is metastable to the decay (conversion) to a hybrid neutron star or to a strange star. The mean lifetime of the metastable configuration dramatically depends on the value of the stellar central pressure. We explore the consequences of the metastability of "massive" neutron stars and of the existence of stable compact quark stars (hybrid neutron stars or strange stars) on the concept of the limiting mass of compact stars. We discuss the implications of our scenario for the interpretation of the stellar mass and radius extracted from the spectra of several X-ray compact sources.

The new paradigm:
two families of "Neutron Stars"

A **1^{st} order quark-deconfinement phase transition** occurs in the core of sufficiently massive **Neutron Stars**

The order of a phase transition: Eherenfest classification

By a phase is meant a physically homogeneous part of a system differing in physical properties from other parts of the system and separated from them by a well defined boundary (interface)

The order of a phase-transition is the order of the lowest derivative of the free energy that is discontinuous at the transition

First-order phase-transition: discontinuity in the first order derivarive of the free energy (e.g. **liquid-vapor phase transition** in water)

Second-order phase-transition: discontinuity in the second order derivarive of the free energy (e.g. **ferromagnetic phase transition**: discontinuity in the magnetic susceptibility)

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

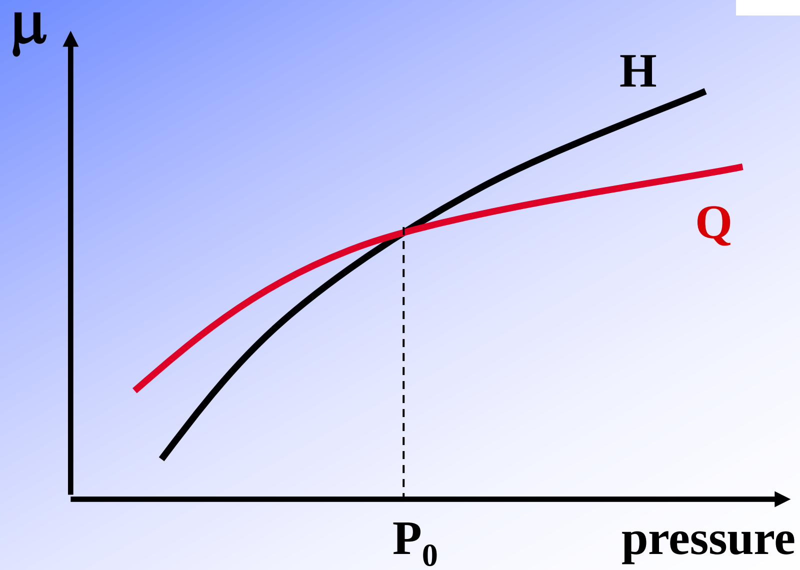
Virtual drops of the stable phase are created by small localized **fluctuations** in the state variables of the **metastable phase**

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 ^{o}C. In the tempearture range (-48.3 — 0) ^{o}C, water is in a metastable phase and ice cristals will form via a nucleation process.

Gibbs' criterion for phase equilibrium



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

$$T_H = T_Q = 0$$

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

Cold deleptonized Neutron Stars
$t \gg t_{cool} \sim$ a few 10^2 s
cooling time

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

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

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

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

Hadronic matter phase is metastable

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

- Oscillation time of a virtual drop in the potential energy barrier:

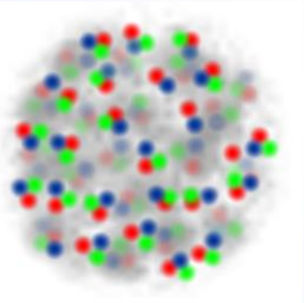
$$\nu_0^{-1} \approx \tau_{strong} \approx 10^{-23}\ \text{sec.} \quad << \quad \tau_{weak}$$

Quark-flavor must be conserved in the early stage of deconfinement

Q*-phase: flavor content is equal to that of β-stable HM at the same pressure and temperature

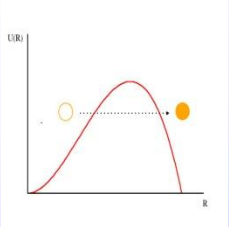
- **Q-phase:** β-stable SQM.

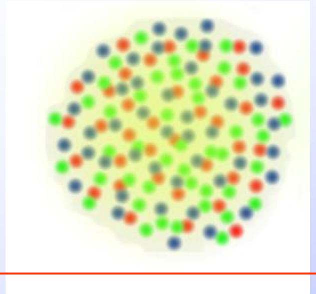
Soon afterwards a critical-size drop of QM is formed, the weak interaction re-establish β-equilibrium



Hadron–phase

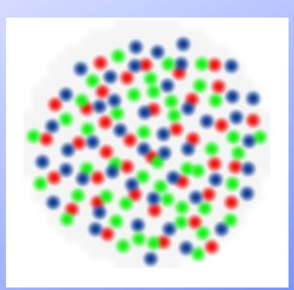
$\tau_S \sim 10^{-23}$ s





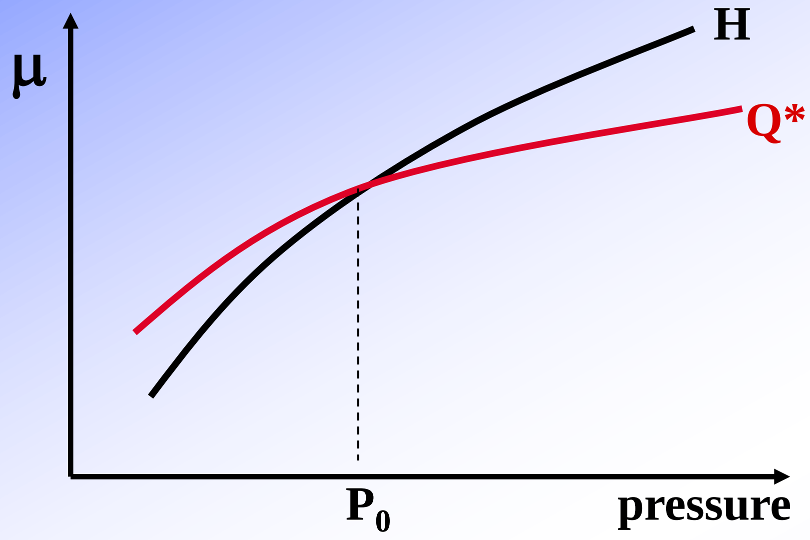
Q*-phase
Non-β-stable quark-matter drop

$\tau_W \sim 10^{-8}$ s



Q-phase

First drop of Q*-matter → **stellar conversion process HS→QS**

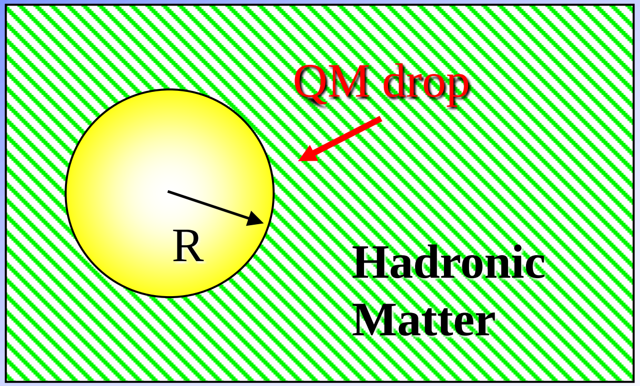


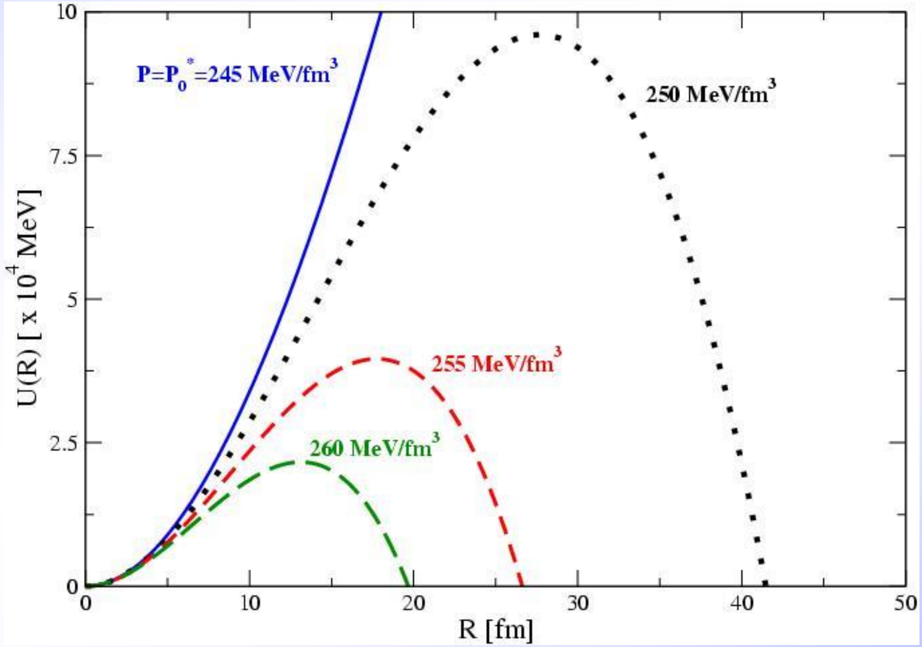
Hadronic Stars with $P_{centr} > P_0$ are **metastable** to the **conversion** **to Quark Stars**

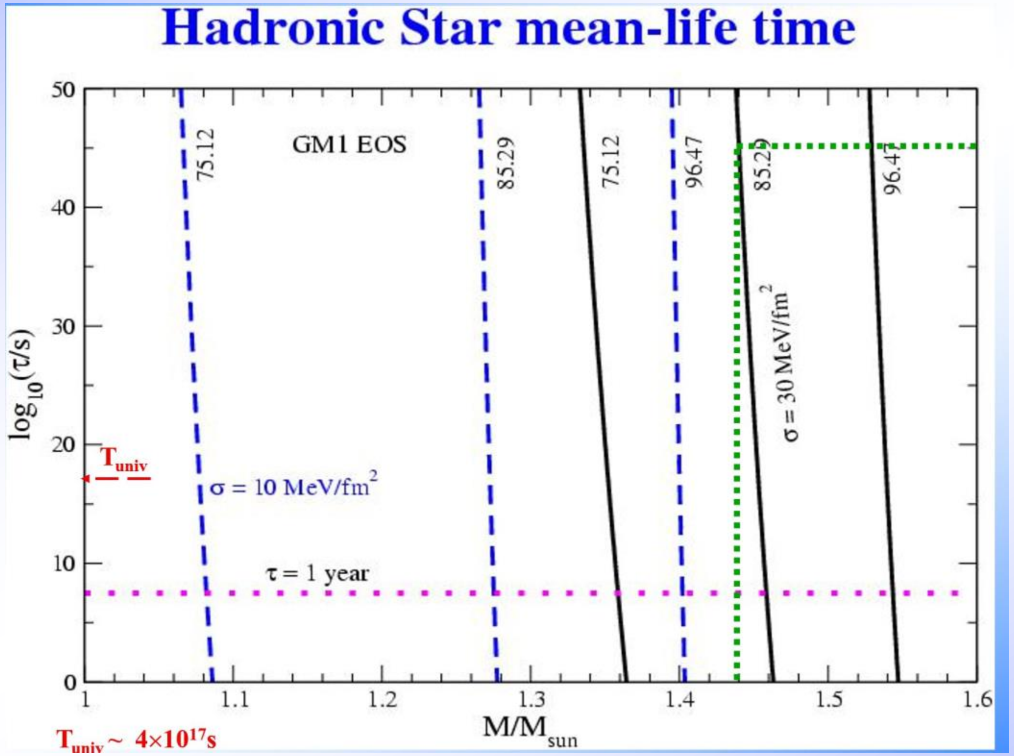
The **mean lifetime** of the **metastable Hadronic Star configuration** is related to the **nucleation time (τ)** of the first **Q*-phase** drop

Quantum nucleation theory

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







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

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

The critical mass of metastable Hadronic Stars

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

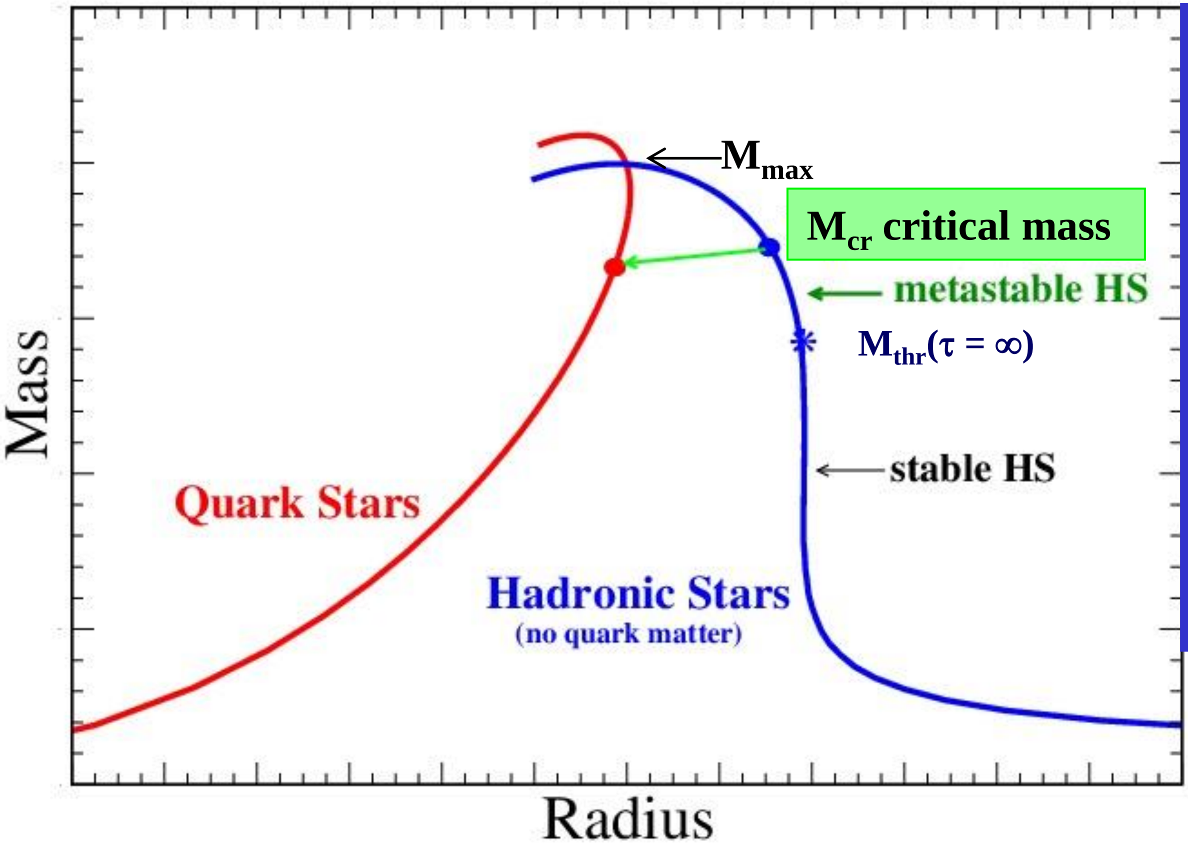
- HS with $M_{thr} < M_{HS} < M_{cr}$ are metastable with $\tau = 1$ yr $\div\ \infty$

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

$\Downarrow$

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

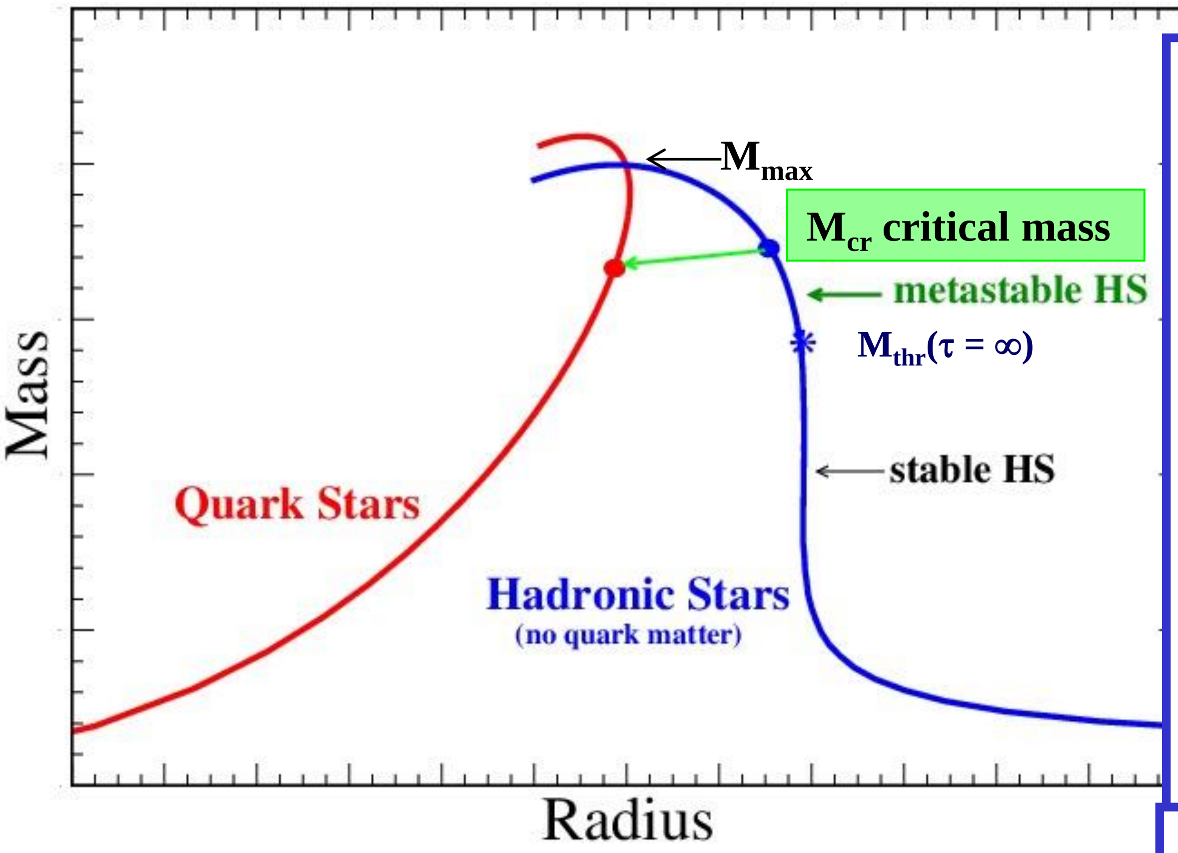
Metastability of Hadronic Stars



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

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, 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
A. Drago, G. Pagliara, EPJA 52 (2016) 41

Metastability of Hadronic Stars



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

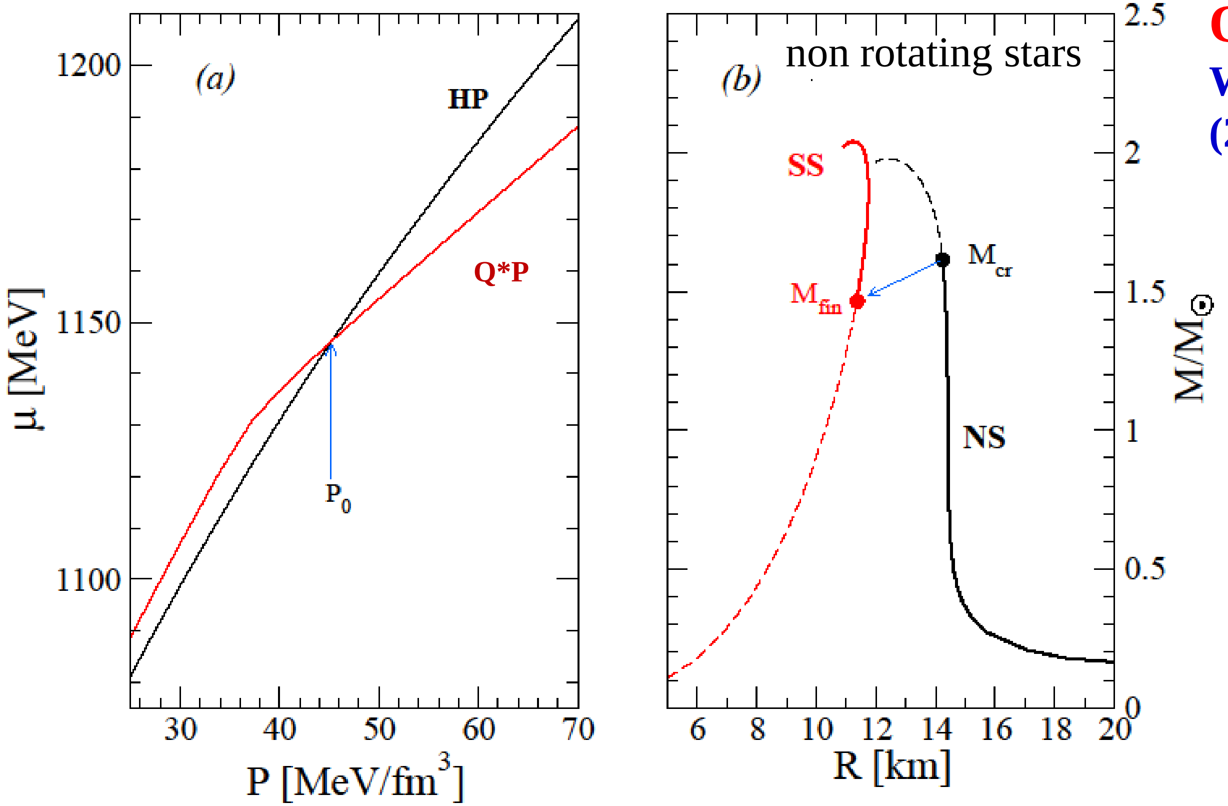
$E_{conv} \sim 10^{53}$ erg

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

Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys
I. Bombaci, I. Parenti, I. Vidaña, Astrophys. Jour. 614 (2004) 314
I. Bombaci, D. Logoteta, C. Providencia, I. Vidaña, Astr. and Astrophys
I. Bombaci, D. Logoteta, I. Vidaña, C. Providencia, EPJ A 52 (2016) 58
A. Drago, G. Pagliara, EPJA 52 (2016) 41

Two families of compact stars



HP: TM1-2(NY) EOS

Providencia, Rabhi, PRC 87 (2013)

QP: extended Bag model

Weissneborn et al. ApJL 740 (2011),

$B_{eff}^{1/4} = 140$ MeV, $a_4 = 0.8$

$M_{max}^{NS} = 1.978\ M_\odot$

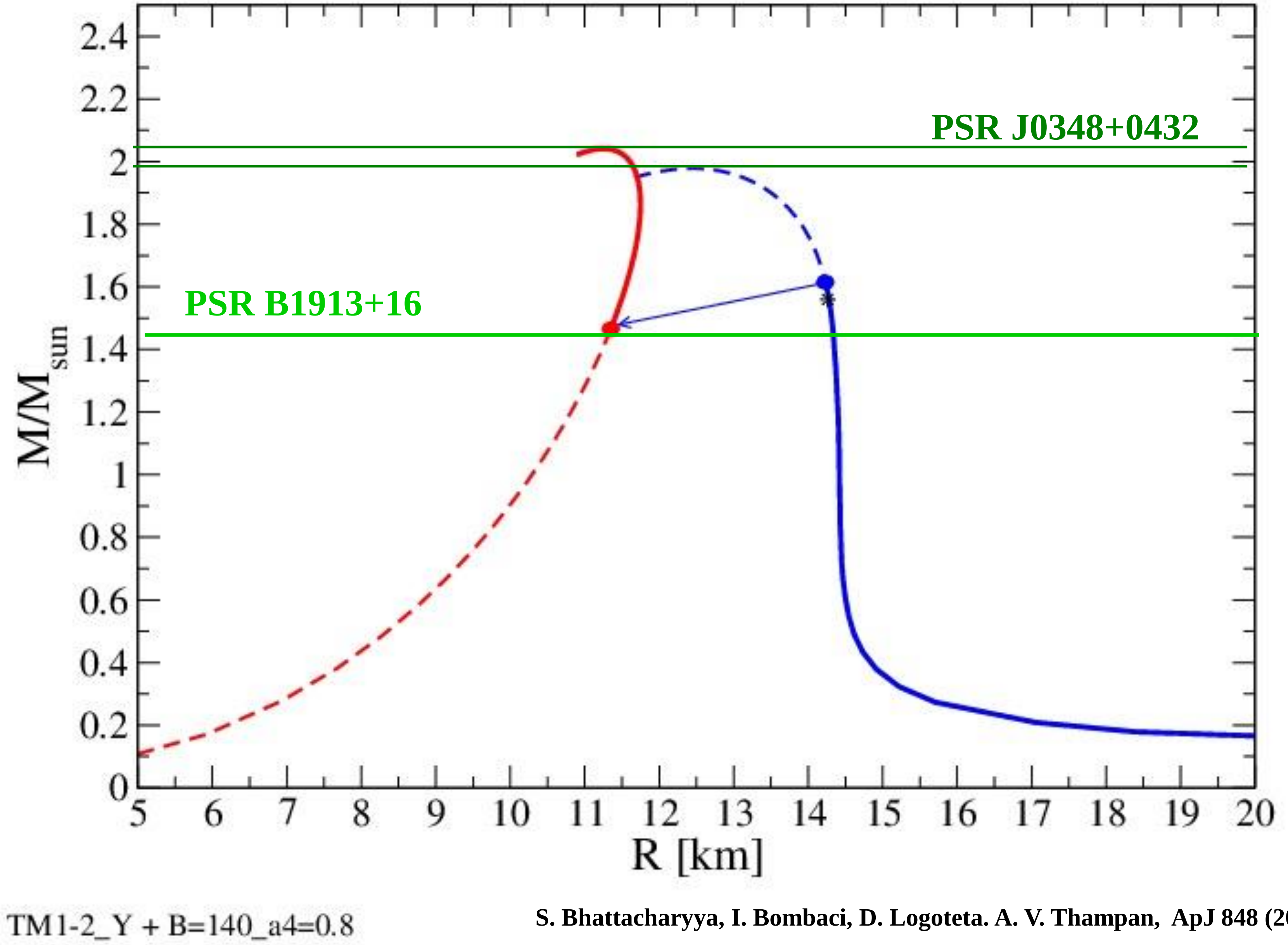
$M_{max}^{SS} = 2.042\ M_\odot$

$M_{cr} = 1.615\ M_\odot$

$M_{fin} = 1.465\ M_\odot$

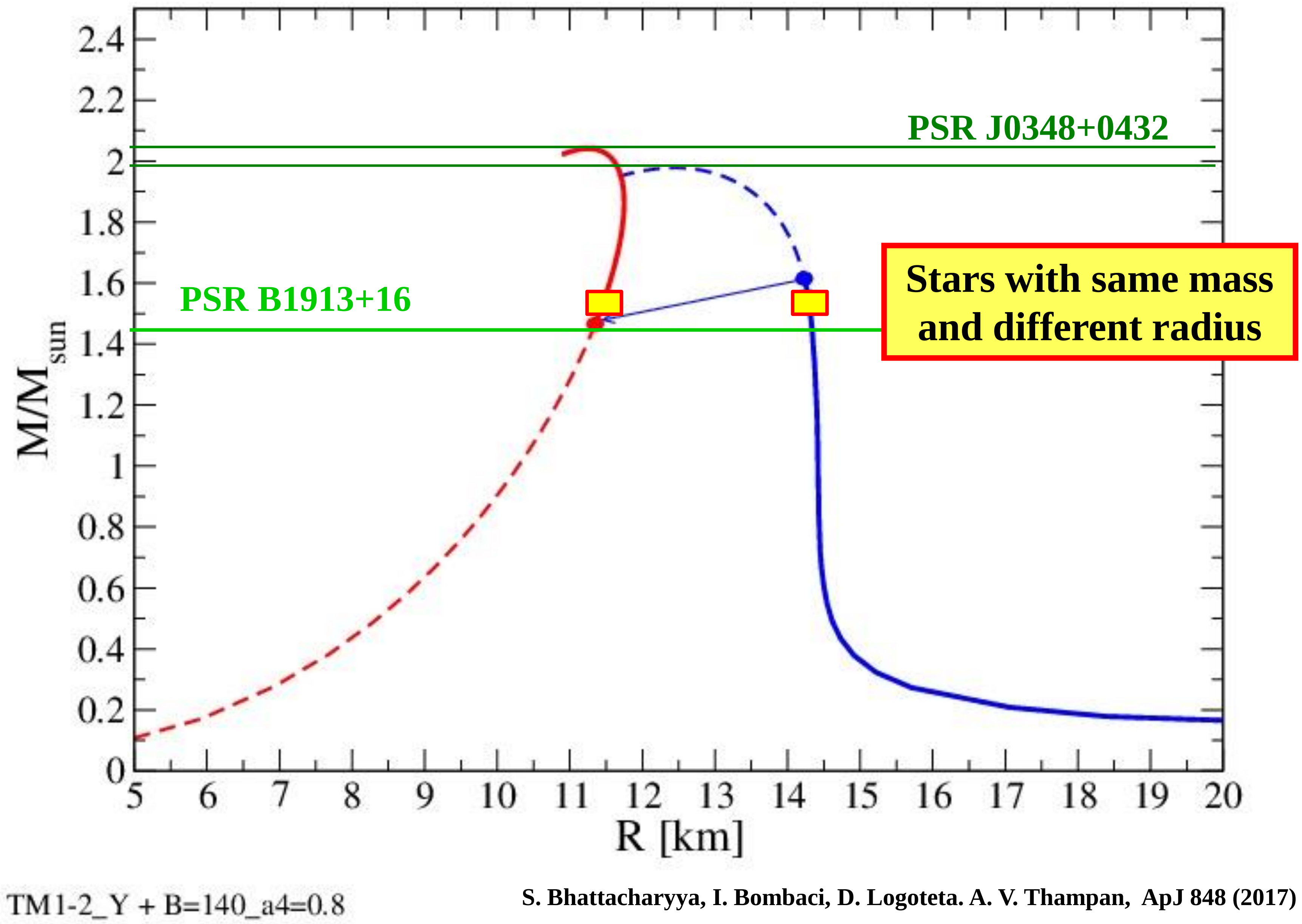
S. Bhattacharyya, I. Bombaci, D. Logoteta. A. V. Thampan, ApJ 848 (2017) 65

Two families of compact stars



S. Bhattacharyya, I. Bombaci, D. Logoteta. A. V. Thampan, ApJ 848 (2017)

Two families of compact stars



S. Bhattacharyya, I. Bombaci, D. Logoteta. A. V. Thampan, ApJ 848 (2017) 65

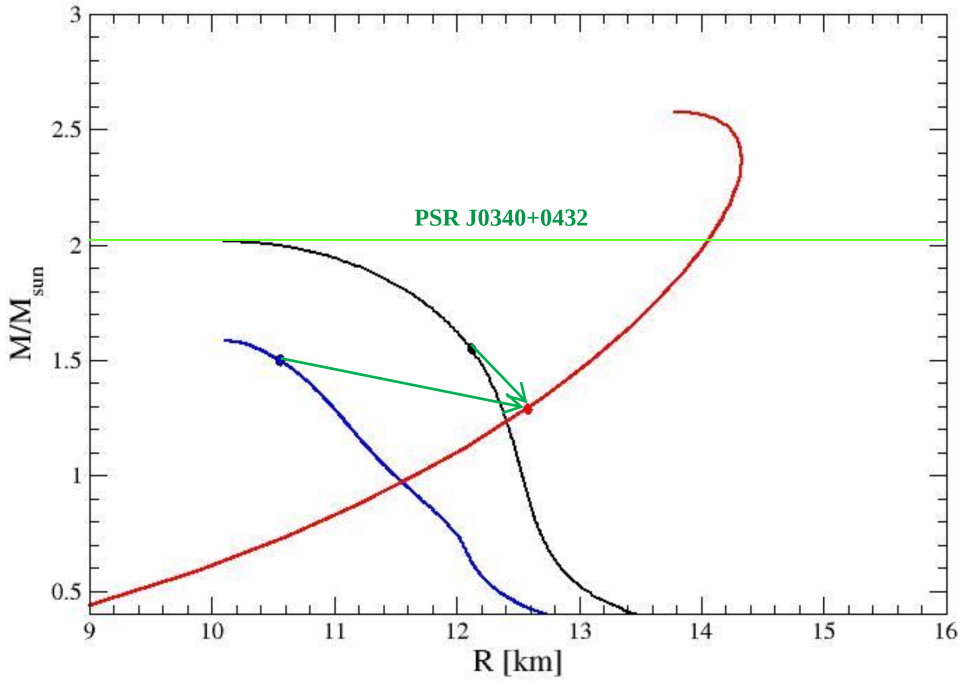
GW190814

Merger of a binary system: 23 $M_\odot$ black hole (BH) + (2.5 – 2.67) $M_\odot$ compact star

The mass of the secondary component lies within the so-called **mass-gap (2.5 – 5) $M_\odot$** between **Neutron Stars** and **Black Holes**.

The secondary component could be the **lightest BH** or the **heaviest NS** ever discovered

A **heavy NS** (stiff nuclear matter EOS) is **not compatible with the constraints on the tidal deformability (stellar radius)** obtained by **GW170817** which **favors softer EOSs**.

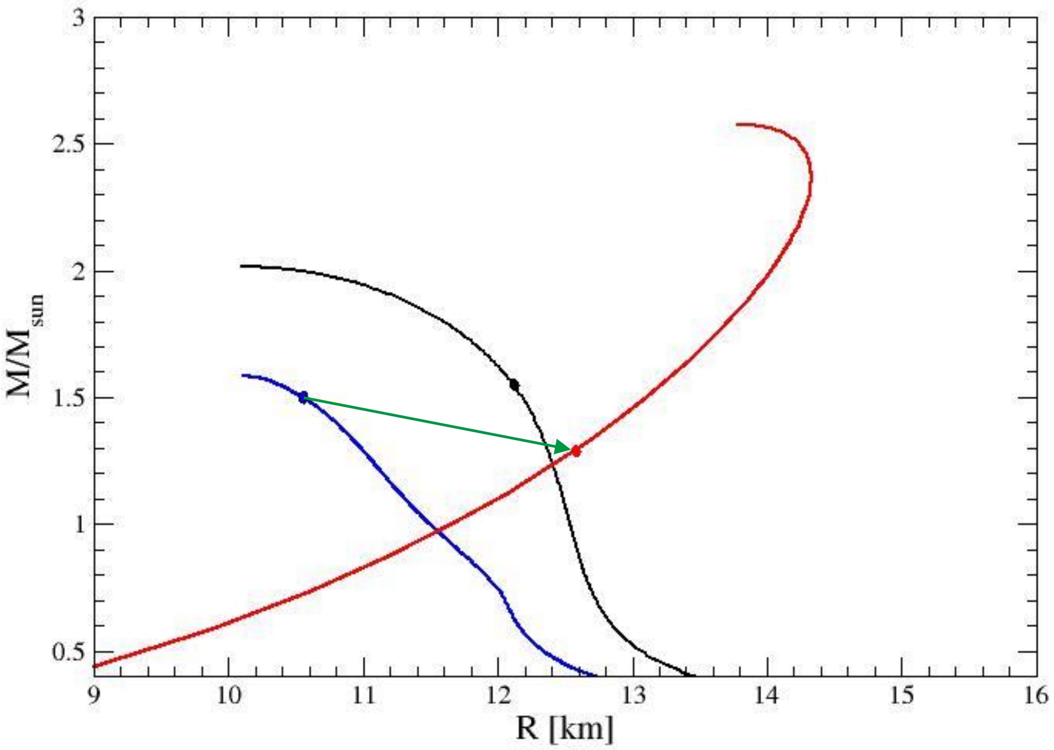


Was GW190814 a black hole – strange quark star system?

I. Bombaci, A. Drago, D. Logoteta, G. Pagliara I. Vidaña, arXiv:2010.1509

Two coexisting families of compact stars: implications for the hyperon puzzle

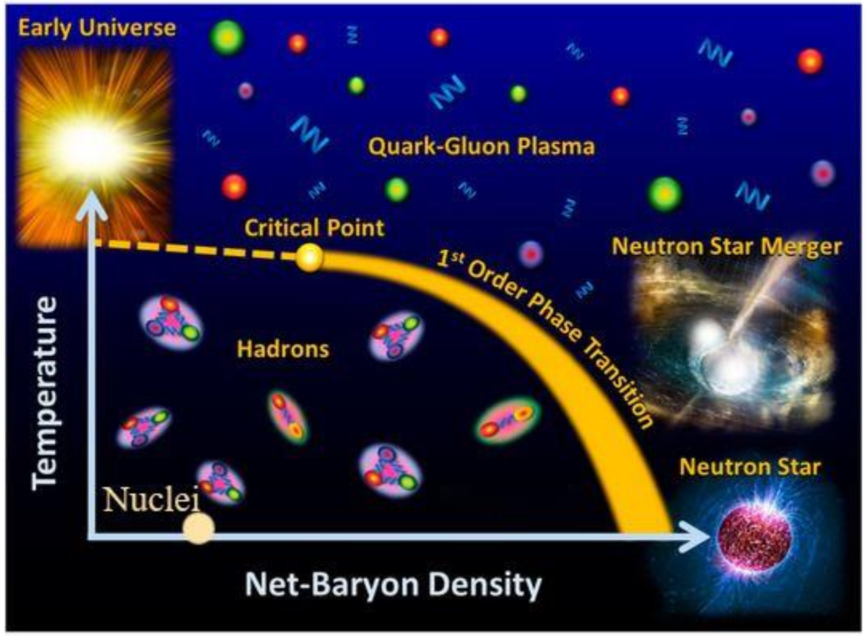
Within the two-families scenario **it is unnecessary to have a stiff EoS for hyperonic matter**, and thus **it is unnecessary to have strongly repulsive two- and three-body hyperonic interactions**, **because compact stars with M ~ 2 $M_{\odot}$ (or even larger values) belong to the QS family**.



In addition hyperon formation in HSs could help the quark **matter nucleation mechanism** which trigger the stellar conversion process.

Probing dense QCD matter in the laboratory

Whether the **quark-deconfinement phase transition** is of the **first-order with a critical endpoint**, or whether it proceedes smothly by a **crossover** is still an open question.



Adapted from P. Senger, and N. Herrmann, Nuclear Physics News, Vol. 28, No 2 (2018) 23.

New dedicated experiments are under construction at future facilities

Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (**FAIR**) in **Darmstadt**,

J-PARC Heavy-Ion-project at the Japan Proton Accelerator Research Complex (**J-PARC**) in **Tōkai**,

Heavy-Ion-program at the Nuclotron-based Ion Collider fAcility (**NICA**) at the Joint Institute for Nuclear Research in **Dubna**.

The prospects in the quest to uncover the correct EoS which describes Neutron Stars look thus very bright.

Special thanks to my collaborators

Domenico Logoteta

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thank you
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謝謝
ngiyabonga
рахмат
teşekkür ederim
Баярлалаа
спасибо
gracias
tapadh leat
dank je
merci
obrigado
bedankt
dziękuję
hvala
mauruuru
sukriya
kop khun krap
go raibh maith agat
mochchakkeram
arigatō
dakujem
мерси
grazie
terima kasih
감사합니다
ありがとう
ευχαριστώ
takk
tack
mersi
barka
welalin
spas
misaotra
matondo
paldies
mahalo
хвала
asante
manana
tenki
djiere dieuf
mamnun
trugarez
shukriya
dhanyavadagalu
diolch
rahmet
tanemirt
xiexie
sulpay
gracies
chnorakaloutioun
najis tuke
kam sah hamnida
didi madloba
mesi
sagolun
dekuji
sobodi
enkosi
bayarlalaa
gracie
köszönöm
kiitos
dankie
faafetai lava
vinaka
спасибі
blagodaram
akun
dankon
aciu
nandi
nanni
murakoze
merce