Hyperons & Neutron Stars

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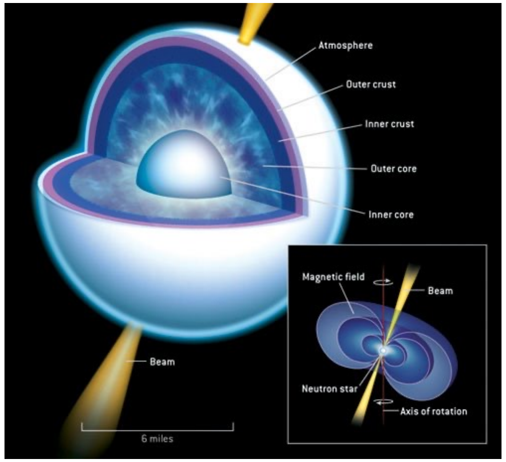
Some known facts about Neutron Stars

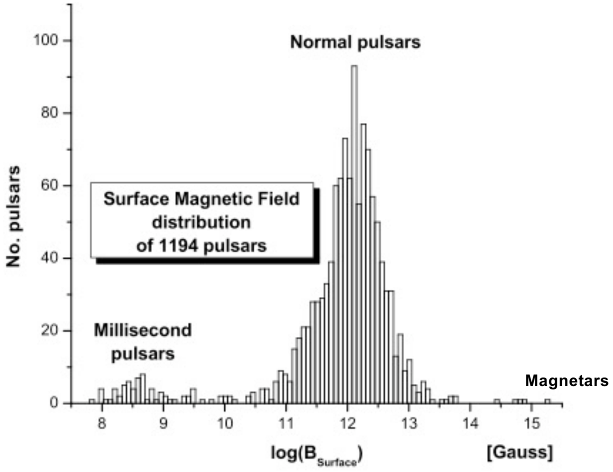
NSs are type of stellar compact remnant resulting from the gravitational collapse of a massive star ($8\ M_\odot < M < 25\ M_\odot$) during a Type II, Ib or Ic supernova event



- Mass: $M \sim 1 - 2\ M_\odot$
- Radius: $R \sim 10 - 12$ km
- Density: $\rho \sim 10^{14} - 10^{15}\ \mathrm{g/cm^3}$

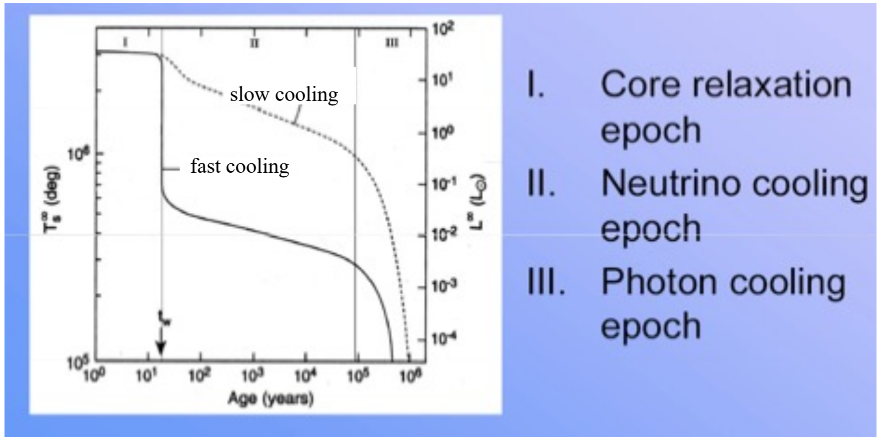
- Baryonic number: $N_b \sim 10^{57}$ ("giant (hyper) nuclei")
- Surface magnetic field: $B \sim 10^{8\ldots16}$ G ($10^{4\ldots12}$ T)

Type of Pulsar	Surface magnetic field
Millisecond	$10^8 - 10^9$ G
Normal	10^{12} G
Magnetar	$10^{14} - 10^{15}$ G

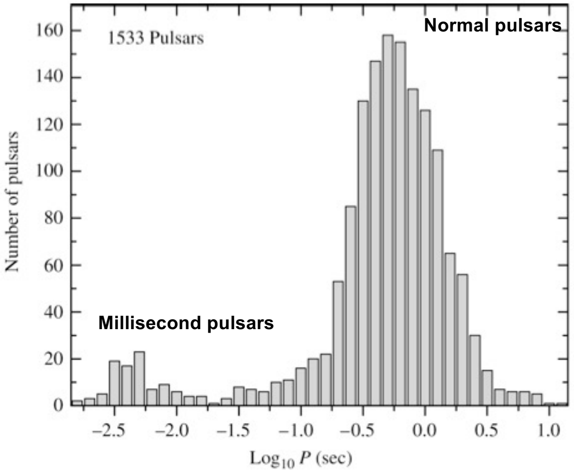


- Electric field: $E \sim 10^{18}$ V/cm
- Temperature: $T \sim 10^{6 \ldots 11}$ K
- Rotational period distribution
  ➔ two types of pulsars:
  - pulsars with $P \sim$ s
  - pulsars with $P \sim$ ms

Shortest rotational period: $P_{B1937+2} = 1.58$ ms until the last discovery: PSR in Terzan 5: $P_{J1748\text{-}2446ad} = 1.39$ ms



I. Core relaxation epoch
II. Neutrino cooling epoch
III. Photon cooling epoch



Recent Measurements of High NS Masses

- PSR J164-2230 (Demorest et al. 2010)

✓ binary system (P=8.68 d)

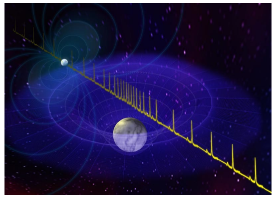
✓ low eccentricity (ε=1.3 x 10^{-6})

✓ companion mass: $\sim 0.5 M_\odot$

✓ pulsar mass: $M = 1.928 \pm 0.017 M_\odot$

In this decade NS with $2M_\odot$ have been observed by measuring Post-Keplerian parameters of their orbits

- Advance of the periastron $\dot{\omega}$
- Shapiro delay (range & shape)
- Orbital decay $\dot{P}_b$
- Grav. redshift & time dilation γ



- PSR J0348+0432 (Antoniadis et al. 2013)

✓ binary system (P=2.46 h)

✓ very low eccentricity

✓ companion mass: $0.172 \pm 0.003 M_\odot$

✓ pulsar mass: $M = 2.01 \pm 0.04 M_\odot$

- MSP J0740+6620 (Cromartie et al. 2020)

✓ binary system (P=4.76 d)

✓ low eccentricity (ε=5.10(3) x 10^{-6})

✓ companion mass: $0.258(8) M_\odot$

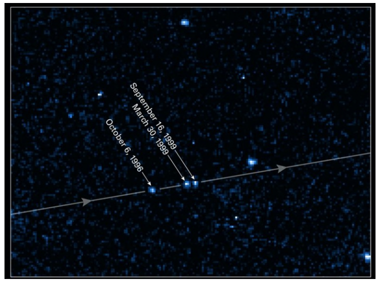
✓ pulsar mass: $M = 2.14^{+0.10}_{-0.0.9} M_\odot$ (68.3% c.i.)

$M = 2.14^{+0.20}_{-0.018} M_\odot$ (95.4% c.i.)

The desired measurement of neutron star radii

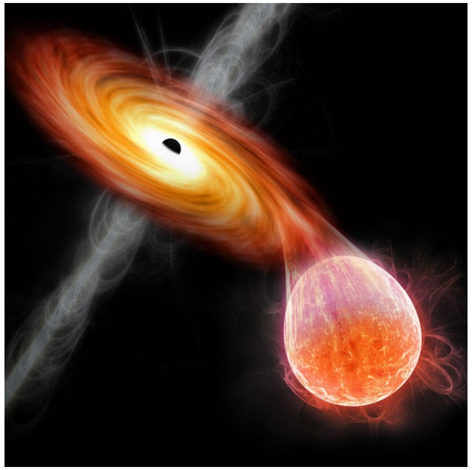
Radii are very difficult to measure because NS:

- ✧ are very small (~ 10 km)
- ✧ are far from us (e.g., the closest NS, RX J185635-3754, is at ~ 200 ly, moving at 100 km/s)



Credit by NASA

A possible way to measure it is to use the thermal emission of low mass X-ray binaries:



NS radius can be obtained from:

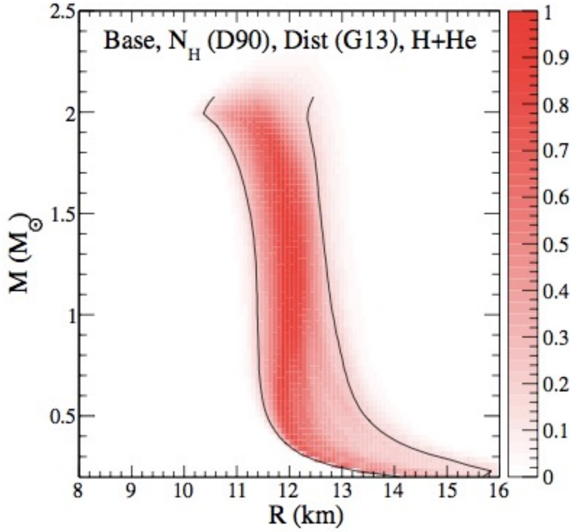
- ✧ Flux measurement +Stefan-Boltzmann's law
- ✧ Temperature (Black body fit+atmosphere model)
- ✧ Distance estimation (difficult)
- ✧ Gravitational redshift z (detection of absorption lines)

$$R_\infty = \sqrt{\frac{FD^2}{\sigma_{SB}T^4}} \rightarrow R_{NS} = \frac{R_\infty}{1+z} = R_\infty\sqrt{1-\frac{2GM}{R_{NS}c^2}}$$

Estimations of Neutron Star Radii from LMXB

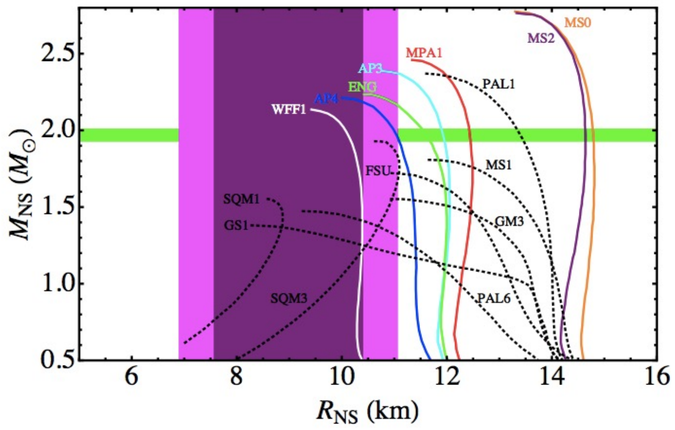
The conclusion from past analysis of the thermal spectrum from 5 quiescent LMXB in globular clusters was controversial

Steiner et al. (2013, 2014)



$$R = 12.0 \pm 1.4 km$$

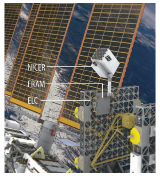
Guillot et al. (2013, 2014)

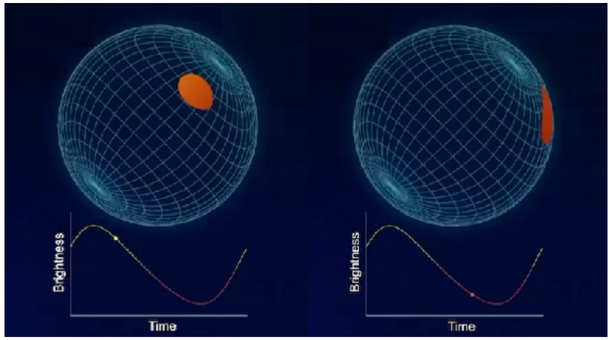


$$R = 9.1^{+1.3}_{-1.5} km$$ 2013 analysis

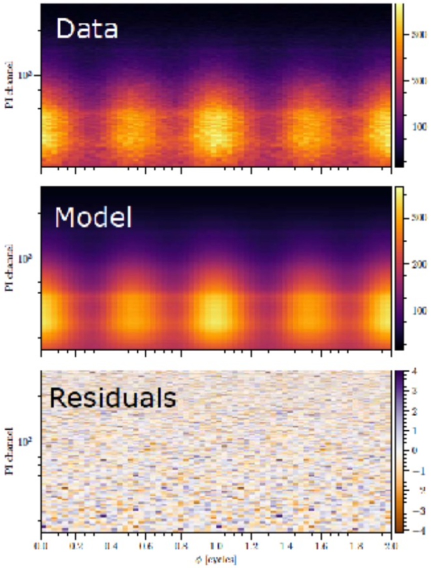
$$R = 9.4 \pm 1.2 km$$ 2014 analysis

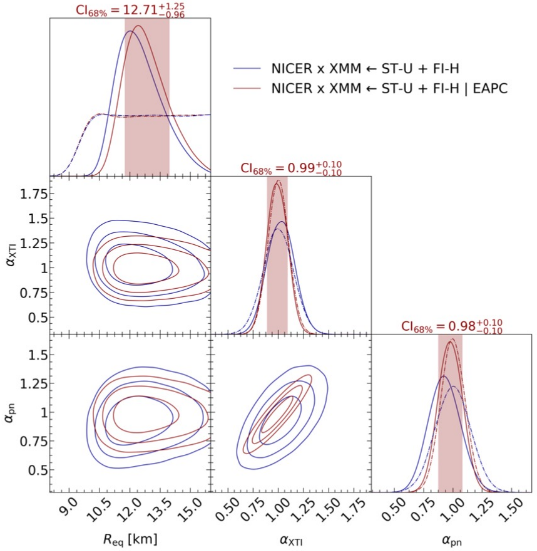
NICER: Neutron Star Interior Composition Explorer





A new way of measuring NS radius by tracking the X-ray emission from “hot spots” on the star’s surface as the star rotates. M/R is extracted by modeling the Pulse Profile of the hot spots





✧ PSR J0740+6620

$$M = 2.072^{+0.067}_{-0.066} M_{\odot}$$

$R = 13.7^{+2.6}_{-1.5}$ km Miller et al., arXiv:2105.06979

$R = 12.39^{+1.30}_{-0.98}$ km Riley et al., arXiv:2105.06980

✧ PSR J0030+0451

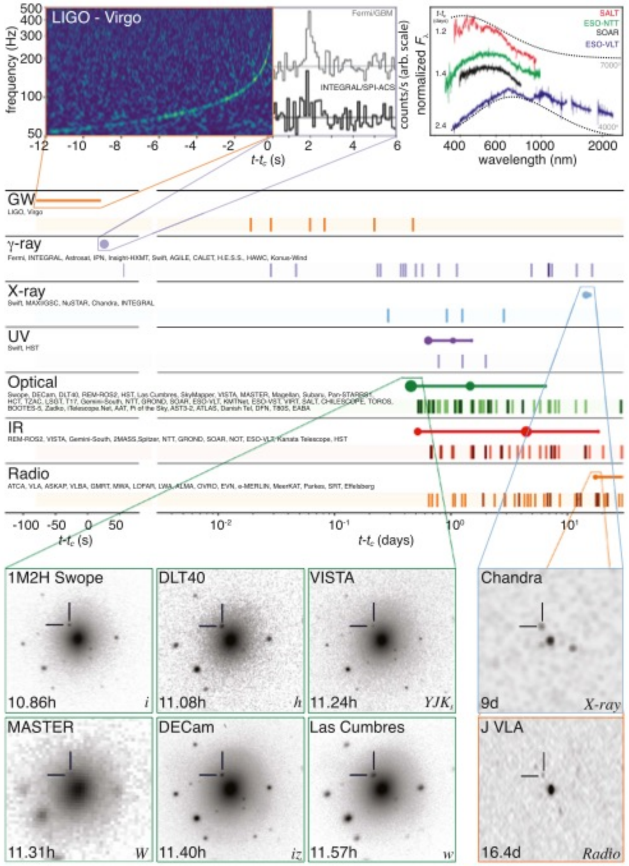
$$M/R = 0.156^{+0.008}_{-0.010}$$

$R = 13.02^{+1.24}_{-1.06}$ km Miller et al., ApJ 887 L24 (2019)

$R = 12.71^{+1.14}_{-1.19}$ km Riley et al., APJ 887 L21 (2019)

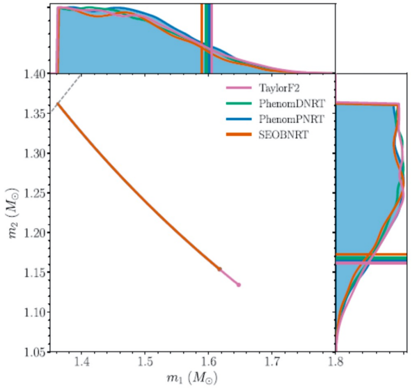
GW170817: the first NS-NS merger

Multi-messenger observations of the event GW170817



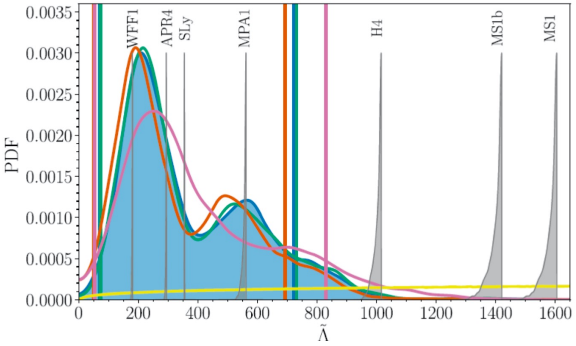
✧ Masses estimated from the chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$



✧ Radius from the tidal deformability

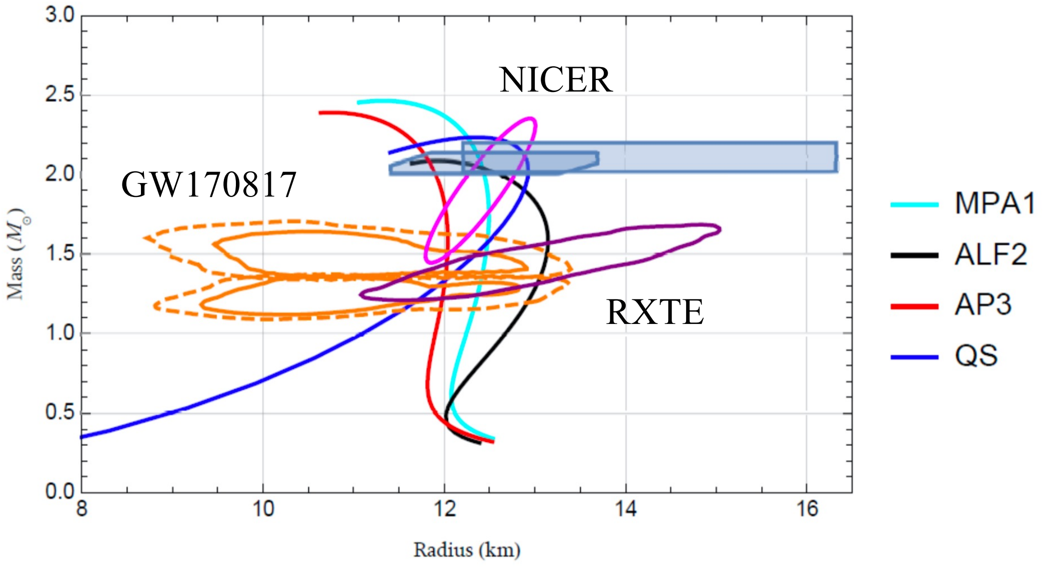
$$\tilde{\Lambda} = \frac{16}{13}\frac{(1+12q)\Lambda_1+(q+12)\Lambda_2}{(1+q)^5}$$



A 1.36$M_\odot$ has a radius of 10.4 km (WFF1), 11.3 km (APR4), 11.7 km (Sly), 12.4 km (MPA1), 14.0 (H4), 14.5 (MS1b) and 14.9 km (MS1)

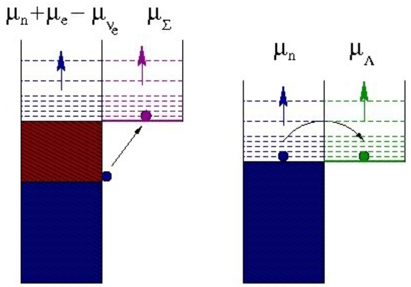
Combined analysis of a few astrophysical data

- ✧ NICER PSR J0740+6620 & PSR J0030+0451 (bands)
- ✧ GW170817 (from tidal deformability, orange solid/dashed lines)
- ✧ Rossi X-ray Timing Explorer (RXTE) results for the cooling tail spectra of 4U1702-429 (violet line)



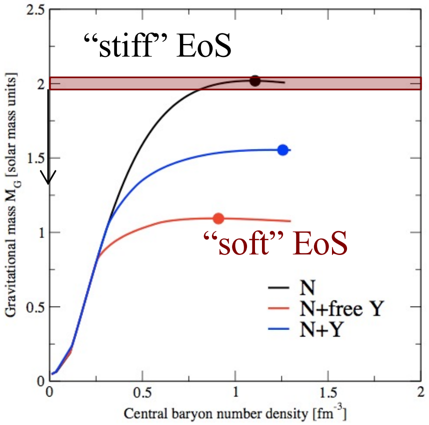
The Hyperon Puzzle: Still An Open Problem ?

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make the conversion of N into Y energetically favorable



But

The relieve of Fermi pressure due to its appearance leads to a softer EoS and, therefore, to a reduction of the mass to values incompatible with observation



Observation of $\sim 2\,M_\odot$ NS → Any reliable EoS of dense matter should predict $M_{max}\left[EoS\right] > 2M_\odot$

Can hyperons be present in the interior of neutron stars in view of this stringent constraint ?

Possible Solutions to the Hyperon Puzzle

The solution requires a mechanism that could eventually provide the additional pressure at high densities needed to make the EoS stiffer and, therefore, M_{max} compatible with current observational limits. Possible mechanisms could come from:

- Two-body YN & YY interactions
  - YY vector meson repulsion: ϕ meson coupled only to hyperons yielding strong repulsion at high ρ
  - Chiral forces: YN from χEFT predicts Λ s.p. potential more repulsive than those from meson exchange
- Hyperonic Three Body Forces

  Natural solution based on the known importance of 3N forces in nuclear physics
- Quark Matter Core

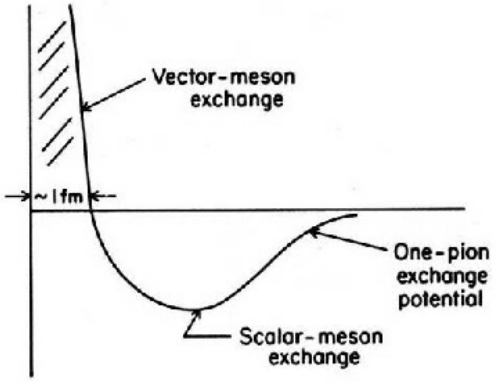
  Phase transition to deconfined QM at densities lower than hyperon threshold

Solution Ia: YY vector meson repulsion

(explored in the context of RMF models)

General Feature:

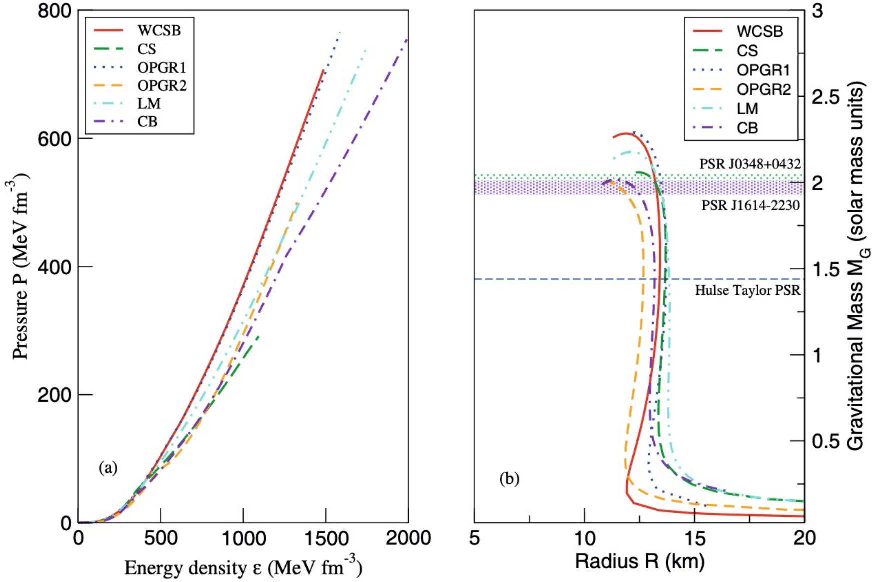
Exchange of scalar mesons generates attraction (softening), but the exchange of vector mesons generates repulsion (stiffening)

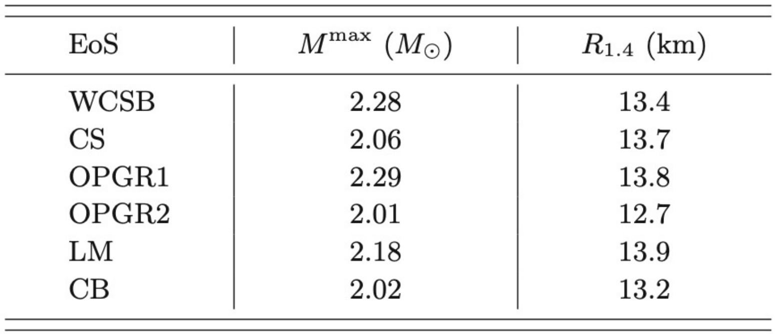


Add vector mesons with hidden strangeness (ϕ) coupled to hyperons yielding a strong repulsive contribution at high densities

Dexhamer & Schramm (2008), Bednarek et al, (2012), Weissenborn et al., (2012), Oertel et al. (2014), Maslov et al. (2015) & many others

The number of works that have explored this solution to the hyperon problem in the last years is too large and, unfortunately, we cannot summarize all of them, and are forced to choose a few as representative of the copious research carried out





EoS	$M^{\max}$ $(M_\odot)$	$R_{1.4}$ (km)
WCSB	2.28	13.4
CS	2.06	13.7
OPGR1	2.29	13.8
OPGR2	2.01	12.7
LM	2.18	13.9
CB	2.02	13.2

WCSB: S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Phys. Rev. C 85, 065802 (2012) 90, 019904(E) (2014)

CS: G. Colucci, A. Sedrakian, Phys. Rev. C 87, 055806 (2013)

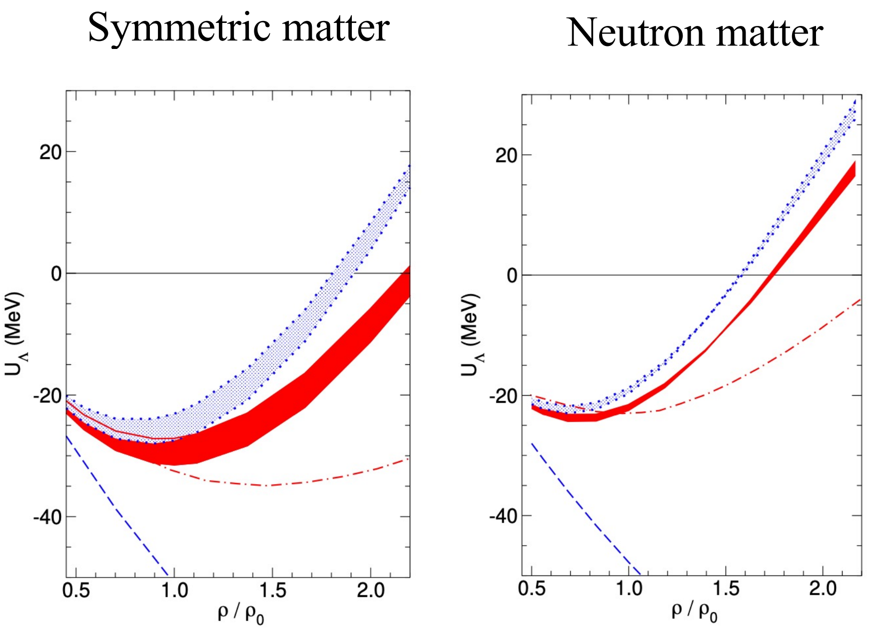
OPGR1,OPGR2: M. Oertel, C. Provid^encia, F. Gulminelli, Ad.R. Raduta, J. Phys. G. 42, 075202 (2015)

LM: L.L. Lopes, D.P. Menezes, Phys. Rev. C 89, 025805 (2014).

CB: P. Char, S. Banik, Phys. Rev. C 90, 015801 (2014)

Solution Ib: χEFT YN interactions

It has been recently shown that YN from χEFT predicts a Λ single-particle potential more repulsive than those from meson exchange going, therefore, in the good direction



Petschauer *et al.*, Front. Phys. 8, 12 (2020)

BHF calculation (continuous choice) with the chiral interactions of the Bonn-Juelich-Munich group

- Red bands: ΛN at NLO (λ=450-500 MeV)
- Blue bands: ΛN + density dependent ΛN from ΛNN
- Dashed curve: Juelich 04 YN interaction
- Dashed-Dotted curve: NSC97f YN interaction

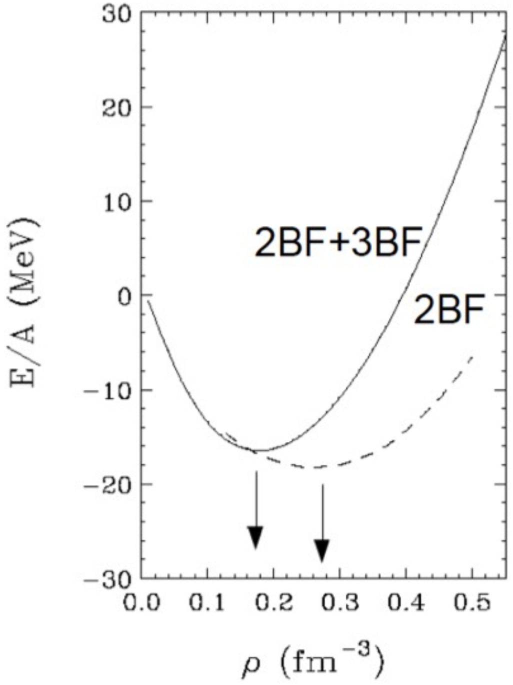
The results in symmetric & neutron matter are promising but a full calculation with chiral interactions under the conditions of β-stability is still missed

Solution II: can Hyperonic TBF solve this puzzle ?

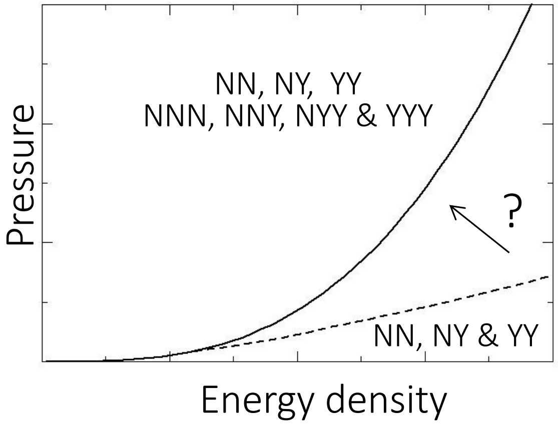
Natural solution based on: Importance of NNN force in Nuclear Physics

(Considered by several authors: Chalk, Gal, Usmani, Bodmer, Takatsuka, Loiseau, Nogami, Bahaduri, Vidaña, Lonardoni,Gerstung)

NNN Force



NNY, NYY & YYY Forces



Can hyperonic TBFs provide enough repulsion at high densities to reach $2M_\odot$?

This idea was suggested even before the observation of neutron stars with $\sim 2M_\odot$ by Takatsuka *et al.* in a couple of papers in 2002 & 2008 because microscoscopic calculations with realistic interactions did not reach even 1.44 $M_\odot$

Eur. Phys. J. A **13**, 213–215 (2002)

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Necessity of extra repulsion in hypernuclear systems: Suggestion from neutron stars

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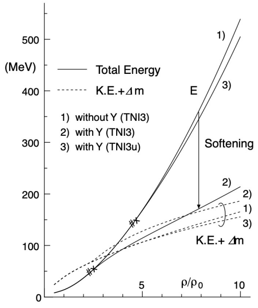
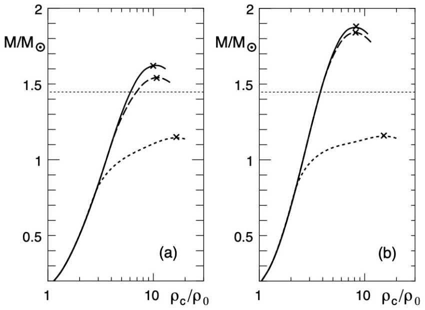
Received: 1 May 2001 / Revised version: 8 July 2001

Abstract. Neutron star models with hyperon-mixed core are studied by a realistic approach to use the YN and the YY interactions consistent with hypernuclear data. From the compatibility of the theoretical maximum mass with the observed neutron star mass 1.44 $M_\odot$ of PSR1913+16, the necessity of some extra repulsion in hypernuclear systems, *e.g.*, a repulsion from three-body force, is stressed. It is noted that the increase of baryon degrees of freedom to avoid the short-range repulsion effectively is an essential mechanism causing the Y-mixed phase.





Progress of Theoretical Physics Supplement No. 174, 2008

Three-Body Force as an "Extra Repulsion" Suggested from Hyperon-Mixed Neutron Stars

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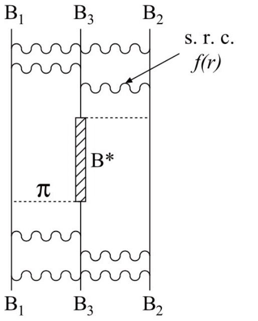
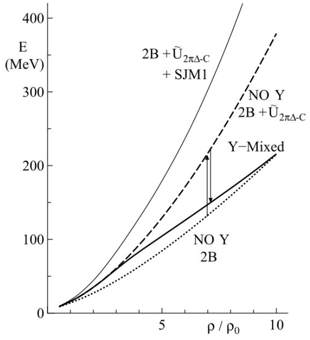
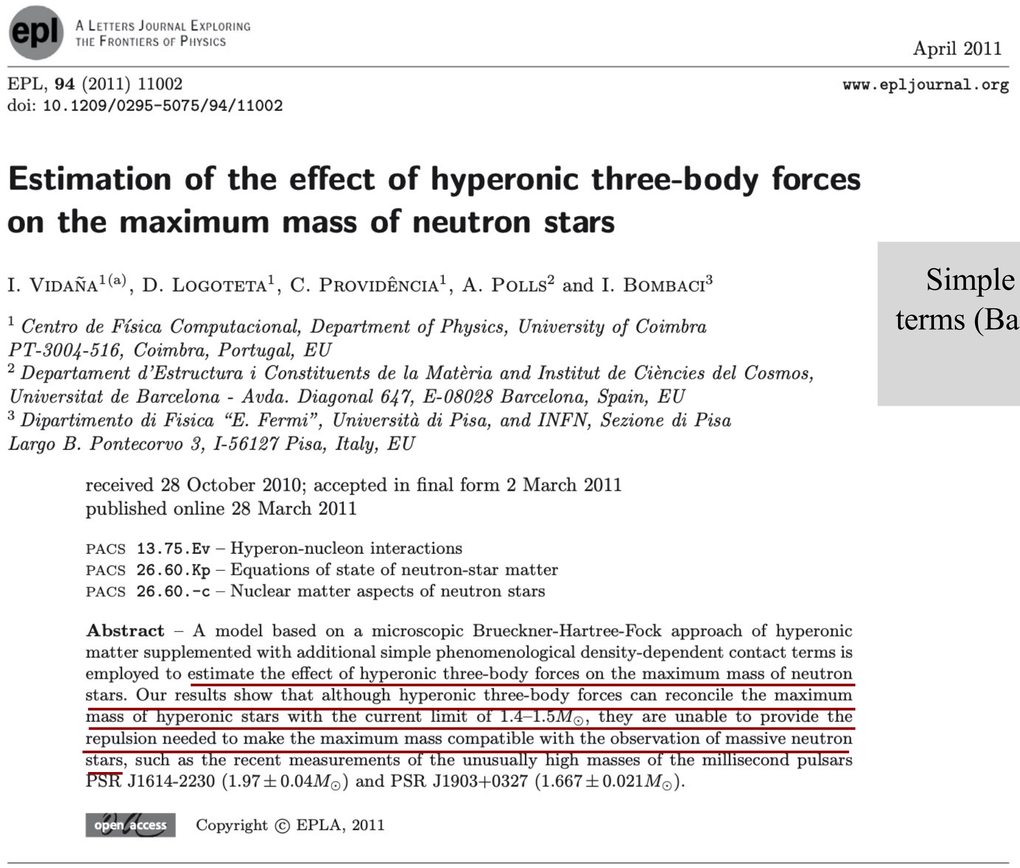
A serious inconsistency between theory and observation for the mass of hyperon-mixed neutron stars strongly suggests the missing of some "extra repulsion" in hypernuclear systems. The mechanism is remarked, and as such microscopic origins of repulsion, the 3-body forces from an extended 2π exchange via isobar Δ excitation type ($2\pi\Delta$) and from a viewpoint of latent effects for two-baryon overlapping in a string-junction quark model (SJM) are tested. It is remarked that the combined effects from these two processes ($2\pi\Delta$+SJM) is a promising candidate to solve the confronting problem, keeping the consistency with the saturation property of nuclear matter.





And after 2010 it has been explored by other authors … (2011)



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Estimation of the effect of hyperonic three-body forces on the maximum mass of neutron stars

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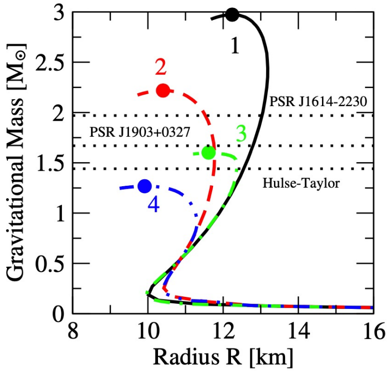
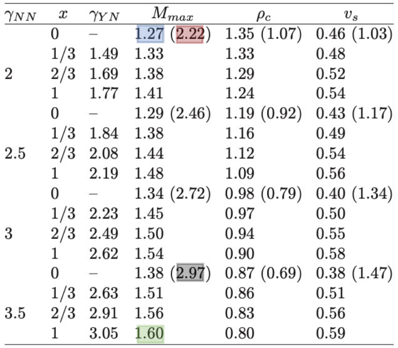
PACS `13.75.Ev` – Hyperon-nucleon interactions
PACS `26.60.Kp` – Equations of state of neutron-star matter
PACS `26.60.-c` – Nuclear matter aspects of neutron stars

Abstract – A model based on a microscopic Brueckner-Hartree-Fock approach of hyperonic matter supplemented with additional simple phenomenological density-dependent contact terms is employed to estimate the effect of hyperonic three-body forces on the maximum mass of neutron stars. Our results show that although hyperonic three-body forces can reconcile the maximum mass of hyperonic stars with the current limit of 1.4–1.5$M_\odot$, they are unable to provide the repulsion needed to make the maximum mass compatible with the observation of massive neutron stars, such as the recent measurements of the unusually high masses of the millisecond pulsars PSR J1614-2230 (1.97 ± 0.04$M_\odot$) and PSR J1903+0327 (1.667 ± 0.021$M_\odot$).





γ_{NN}	x	γ_{YN}	M_{max}	ρ_c	v_s
	0	–	1.27 (2.22)	1.35 (1.07)	0.46 (1.03)
	1/3	1.49	1.33	1.33	0.48
2	2/3	1.69	1.38	1.29	0.52
	1	1.77	1.41	1.24	0.54
	0	–	1.29 (2.46)	1.19 (0.92)	0.43 (1.17)
	1/3	1.84	1.38	1.16	0.49
2.5	2/3	2.08	1.44	1.12	0.54
	1	2.19	1.48	1.09	0.56
	0	–	1.34 (2.72)	0.98 (0.79)	0.40 (1.34)
	1/3	2.23	1.45	0.97	0.50
3	2/3	2.49	1.50	0.94	0.55
	1	2.62	1.54	0.90	0.58
	0	–	1.38 (2.97)	0.87 (0.69)	0.38 (1.47)
	1/3	2.63	1.51	0.86	0.51
3.5	2/3	2.91	1.56	0.83	0.56
	1	3.05	1.60	0.80	0.59

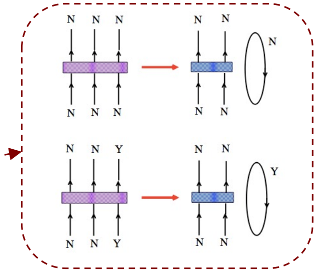
Simple contact density dependent Skyrme-like terms (Balberg & Gal NPA (1997)) that account for

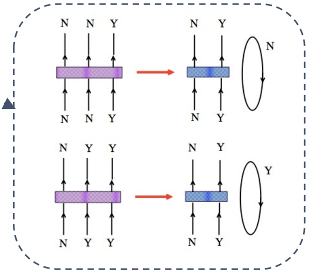
NNN, NNY & NYY

$$\varepsilon_{CT} = a_{NN}\rho_N^2 + b_{NN}\rho_N^{\gamma_{NN}}$$

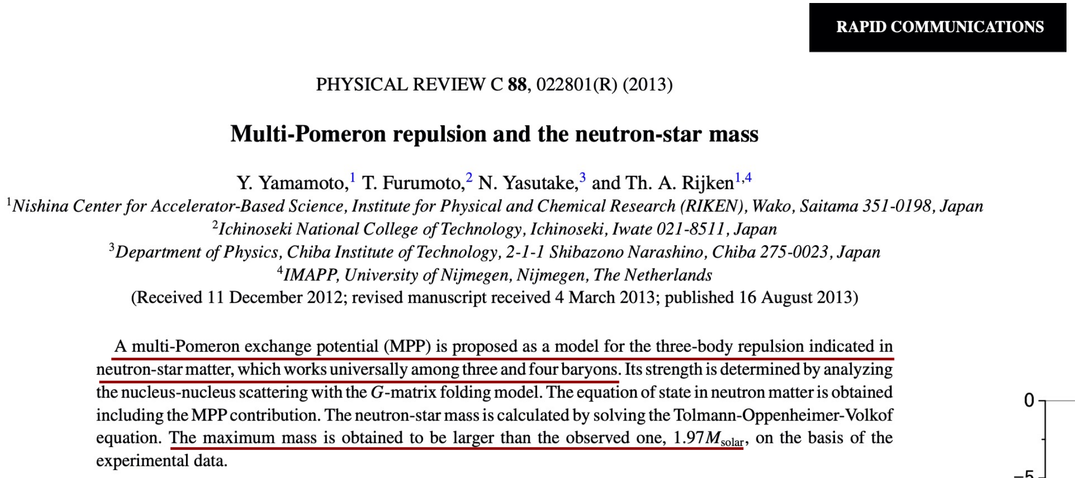
$$+a_{\Lambda N}\rho_\Lambda\rho_N + b_{\Lambda N}\rho_\Lambda\rho_N\left(\frac{\rho_\Lambda^{\gamma_{\Lambda N}}+\rho_N^{\gamma_{\Lambda N}}}{\rho_\Lambda+\rho_N}\right)$$

$$+a_{\Sigma N}\rho_\Sigma\rho_N + b_{\Sigma N}\rho_\Sigma\rho_N\left(\frac{\rho_\Sigma^{\gamma_{\Sigma N}}+\rho_N^{\gamma_{\Sigma N}}}{\rho_\Sigma+\rho_N}\right)$$





And after 2010 it has been explored by other authors … (2013-14)



RAPID COMMUNICATIONS

PHYSICAL REVIEW C **88**, 022801(R) (2013)

Multi-Pomeron repulsion and the neutron-star mass

Y. Yamamoto,[1] T. Furumoto,[2] N. Yasutake,[3] and Th. A. Rijken[1,4]

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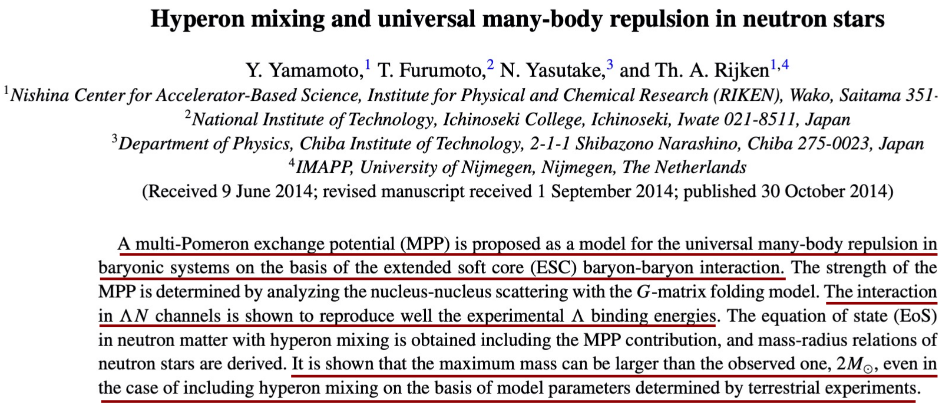
(Received 11 December 2012; revised manuscript received 4 March 2013; published 16 August 2013)

A multi-Pomeron exchange potential (MPP) is proposed as a model for the three-body repulsion indicated in neutron-star matter, which works universally among three and four baryons. Its strength is determined by analyzing the nucleus-nucleus scattering with the *G*-matrix folding model. The equation of state in neutron matter is obtained including the MPP contribution. The neutron-star mass is calculated by solving the Tolmann-Oppenheimer-Volkof equation. The maximum mass is obtained to be larger than the observed one, $1.97 M_{\mathrm{solar}}$, on the basis of the experimental data.



Hyperon mixing and universal many-body repulsion in neutron stars

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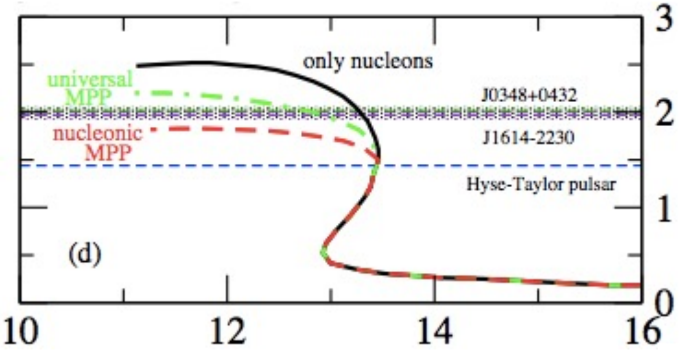
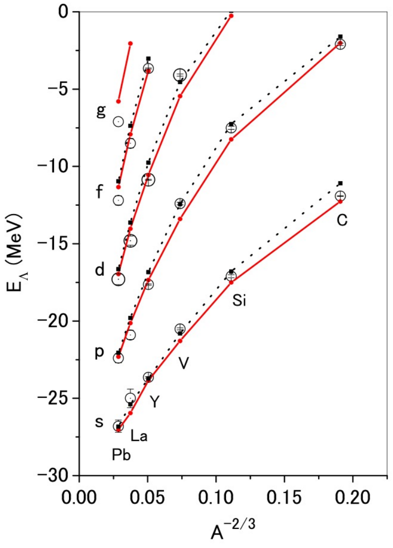
A multi-Pomeron exchange potential (MPP) is proposed as a model for the universal many-body repulsion in baryonic systems on the basis of the extended soft core (ESC) baryon-baryon interaction. The strength of the MPP is determined by analyzing the nucleus-nucleus scattering with the *G*-matrix folding model. The interaction in ΛN channels is shown to reproduce well the experimental Λ binding energies. The equation of state (EoS) in neutron matter with hyperon mixing is obtained including the MPP contribution, and mass-radius relations of neutron stars are derived. It is shown that the maximum mass can be larger than the observed one, $2M_{\odot}$, even in the case of including hyperon mixing on the basis of model parameters determined by terrestrial experiments.

Model: ESC+MPP+TNA





U$_\Lambda$(0) at saturation

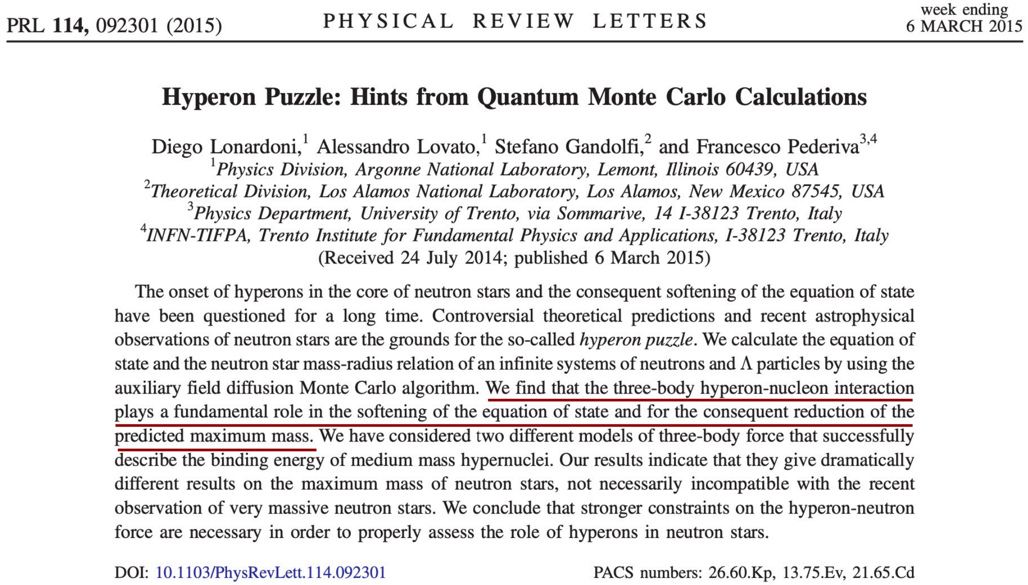
	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	D	U_Λ
ESC	−13.3	−26.7	2.6	0.2	1.8	−3.2	−1.6	−40.0
MPa	−13.6	−25.9	3.4	0.4	2.1	−1.7	−2.7	−38.1
MPb	−13.6	−26.0	3.4	0.4	2.1	−1.8	−2.7	−38.3
MPc	−13.4	−25.1	3.2	0.3	2.0	−2.1	−2.4	−37.4

Energy spectra of $^{89}{}_{\Lambda}$Y

	s	p	d	f
MPa	−23.8	−17.4	−10.6	−3.8
	(1.27)	(1.23)	(1.16)	(1.08)
ESC	−23.7	−16.8	−9.8	−3.0
	(1.28)	(1.23)	(1.17)	(1.09)
Expt.	−23.7	−17.6	−10.9	−3.7

Moderate TBF repulsion leads
to maximum mass ~ $2M_{\odot}$

And after 2010 it has been explored by other authors … (2015)



PRL **114,** 092301 (2015) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2015

Hyperon Puzzle: Hints from Quantum Monte Carlo Calculations

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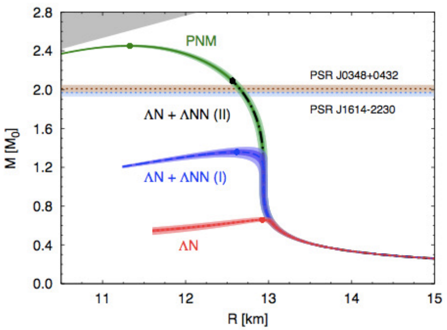
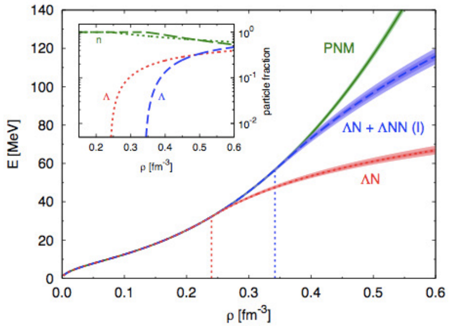
(Received 24 July 2014; published 6 March 2015)

The onset of hyperons in the core of neutron stars and the consequent softening of the equation of state have been questioned for a long time. Controversial theoretical predictions and recent astrophysical observations of neutron stars are the grounds for the so-called *hyperon puzzle*. We calculate the equation of state and the neutron star mass-radius relation of an infinite systems of neutrons and Λ particles by using the auxiliary field diffusion Monte Carlo algorithm. We find that the three-body hyperon-nucleon interaction plays a fundamental role in the softening of the equation of state and for the consequent reduction of the predicted maximum mass. We have considered two different models of three-body force that successfully describe the binding energy of medium mass hypernuclei. Our results indicate that they give dramatically different results on the maximum mass of neutron stars, not necessarily incompatible with the recent observation of very massive neutron stars. We conclude that stronger constraints on the hyperon-neutron force are necessary in order to properly assess the role of hyperons in neutron stars.

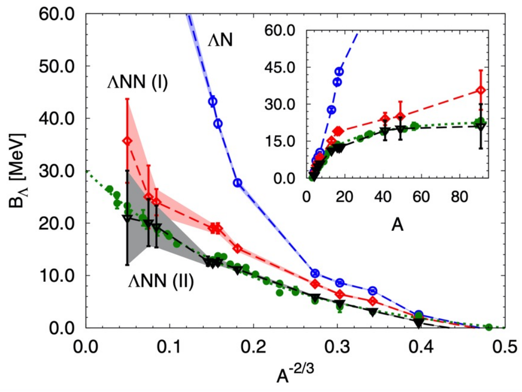
DOI: 10.1103/PhysRevLett.114.092301 PACS numbers: 26.60.Kp, 13.75.Ev, 21.65.Cd



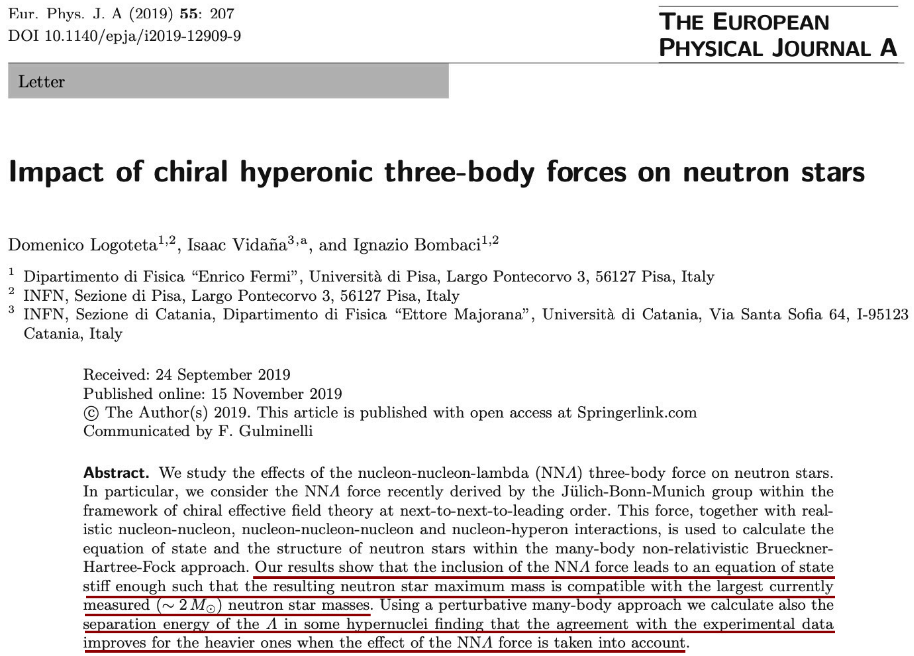


- ✧ NS matter described as mixture of neutrons & Λ's
- ✧ Simple interaction models: Av8'+UIX (nn,nnn) & Bodmer-Usmani (NΛ) potential, NNΛ (2π exchange + phenomenological repulsive term)
- ✧ The only NNΛ able to give $2M_\odot$ leads to the total disappearance of Λ in NS, but this is in fact just pure neutron matter
- ✧ Very large NNΛ repulsion consequence of the fact that they need to compensate the very large attraction of the YN interaction ($U_\Lambda(0) \sim -100$ MeV) to reproduce the binding energies of hypernuclei

Λ separation energies of the s-wave state



And after 2010 it has been explored by other authors … (2019)



Eur. Phys. J. A (2019) **55**: 207
DOI 10.1140/epja/i2019-12909-9

THE EUROPEAN PHYSICAL JOURNAL A

Letter

Impact of chiral hyperonic three-body forces on neutron stars

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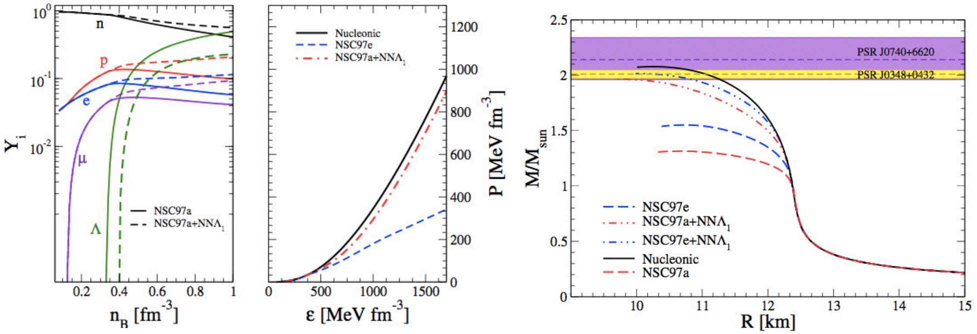
Received: 24 September 2019

Communicated by F. Gulminelli

Abstract. We study the effects of the nucleon-nucleon-lambda (NNΛ) three-body force on neutron stars. In particular, we consider the NNΛ force recently derived by the Jülich-Bonn-Munich group within the framework of chiral effective field theory at next-to-next-to-leading order. This force, together with realistic nucleon-nucleon, nucleon-nucleon-nucleon and nucleon-hyperon interactions, is used to calculate the equation of state and the structure of neutron stars within the many-body non-relativistic Brueckner-Hartree-Fock approach. Our results show that the inclusion of the NNΛ force leads to an equation of state stiff enough such that the resulting neutron star maximum mass is compatible with the largest currently measured $(\sim 2\,M_\odot)$ neutron star masses. Using a perturbative many-body approach we calculate also the separation energy of the Λ in some hypernuclei finding that the agreement with the experimental data improves for the heavier ones when the effect of the NNΛ force is taken into account.

EPJ A Highlight - Towards the solution of the "hyperon puzzle"

"Even if the comparison with the observation still shows some tension, this is the first work showing without any ad-hoc adjustment of phenomenological parameters that the presence of hyperons in the core can be compatible with hyper-massive neutron star"

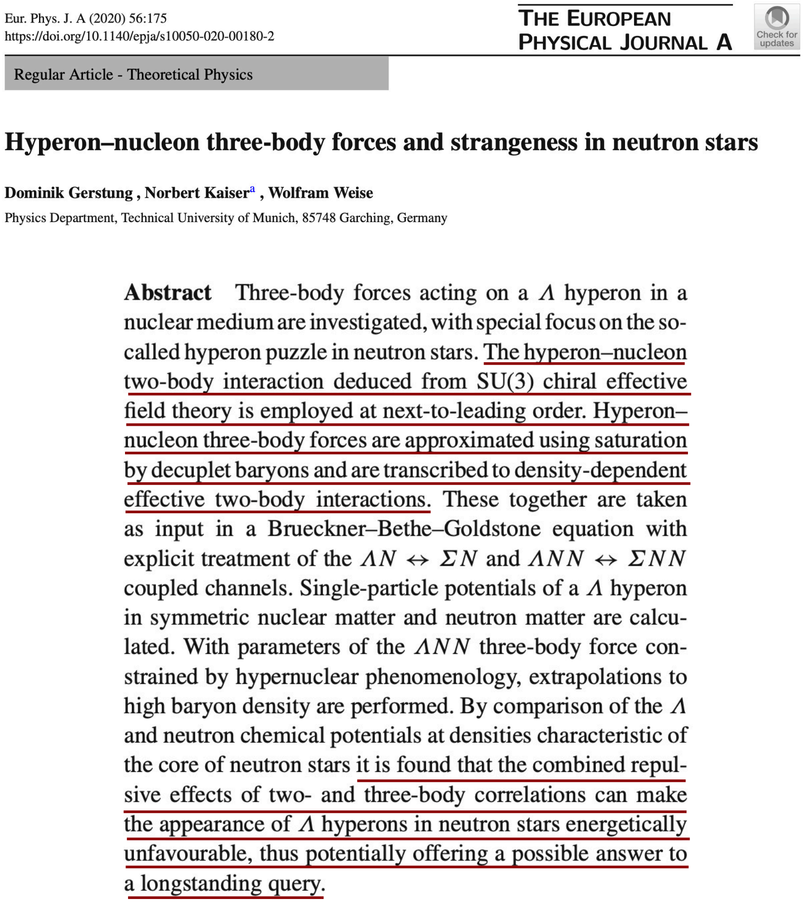


- NS matter described as a mixture of n, p, e$^-$, μ$^-$ & Λ's in β-equilibrium
- χEFT (NN, NNN, NNΛ) + meson-exchange (NY)
- Even if the concentration of Λ's is strongly reduced they are still present in the interior of a 2M$_\odot$ NS
- Moderate NNΛ repulsion (~ 10 MeV at saturation)

Λ separation energies of the s-wave state (not adjusted)

	$^{41}_{\Lambda}$Ca	$^{91}_{\Lambda}$Zr	$^{209}_{\Lambda}$Pb
NSC97a	23.0	31.3	38.8
NSC97a+NNΛ_1	14.9	21.1	26.8
NSC97a+NNΛ_2	13.3	19.3	24.7
NSC97e	24.2	32.3	39.5
NSC97e+NNΛ_1	16.1	22.3	27.9
NSC97e+NNΛ_2	14.7	20.7	26.1
Exp.	18.7(1.1)†	23.6(5)	26.9(8)

And after 2010 it has been explored by other authors … (2020)



Eur. Phys. J. A (2020) 56:175
https://doi.org/10.1140/epja/s10050-020-00180-2

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

Hyperon–nucleon three-body forces and strangeness in neutron stars

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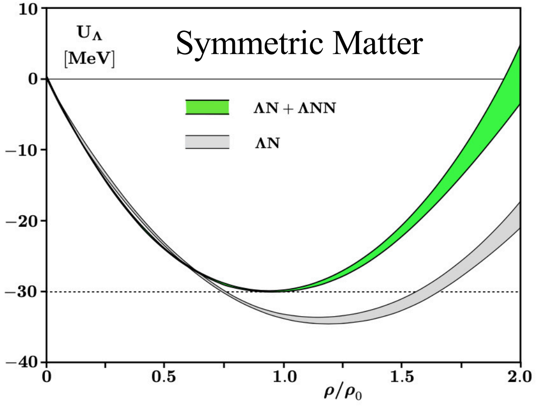
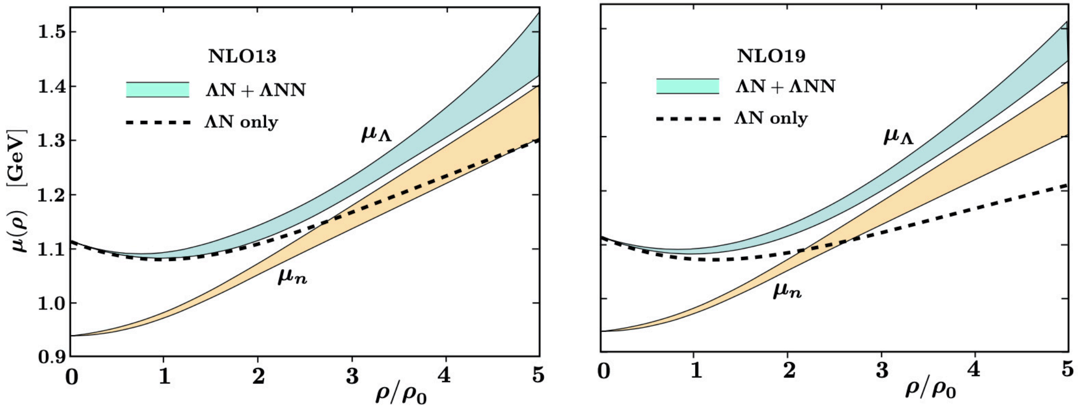
Physics Department, Technical University of Munich, 85748 Garching, Germany

Abstract Three-body forces acting on a Λ hyperon in a nuclear medium are investigated, with special focus on the so-called hyperon puzzle in neutron stars. The hyperon–nucleon two-body interaction deduced from SU(3) chiral effective field theory is employed at next-to-leading order. Hyperon–nucleon three-body forces are approximated using saturation by decuplet baryons and are transcribed to density-dependent effective two-body interactions. These together are taken as input in a Brueckner–Bethe–Goldstone equation with explicit treatment of the $\Lambda N \leftrightarrow \Sigma N$ and $\Lambda NN \leftrightarrow \Sigma NN$ coupled channels. Single-particle potentials of a Λ hyperon in symmetric nuclear matter and neutron matter are calculated. With parameters of the ΛNN three-body force constrained by hypernuclear phenomenology, extrapolations to high baryon density are performed. By comparison of the Λ and neutron chemical potentials at densities characteristic of the core of neutron stars it is found that the combined repulsive effects of two- and three-body correlations can make the appearance of Λ hyperons in neutron stars energetically unfavourable, thus potentially offering a possible answer to a longstanding query.

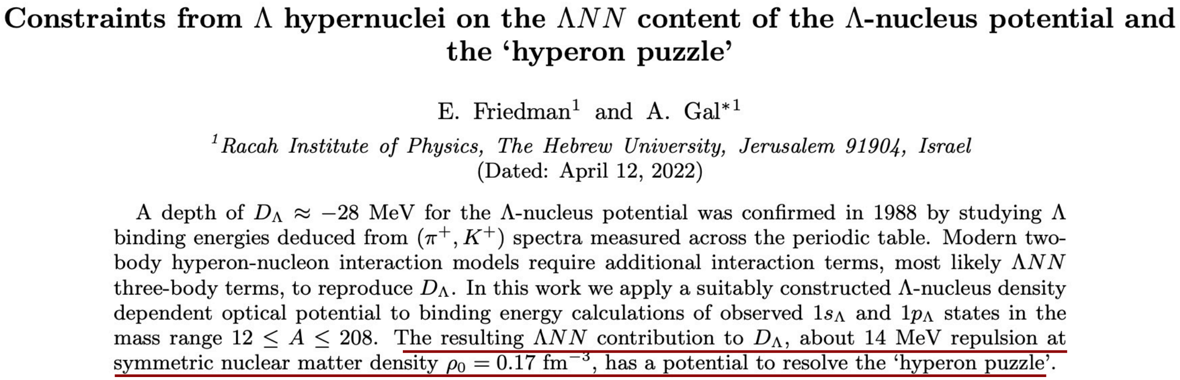
(see Weise's talk)

- ✧ BHF calculation with χEFT NN, NNN, NY NNY forces
- ✧ Calculations made only in symmetric & neutron mater
- ✧ Moderate ΛNN repulsion
  (~ 5 MeV at ρ_0)
- ✧ The results indicate the appearance of Λ in NS energetically unfavorable. But only neutrons & Λ are considered. Conclusions may change in a more realistic scenario





A final comment …



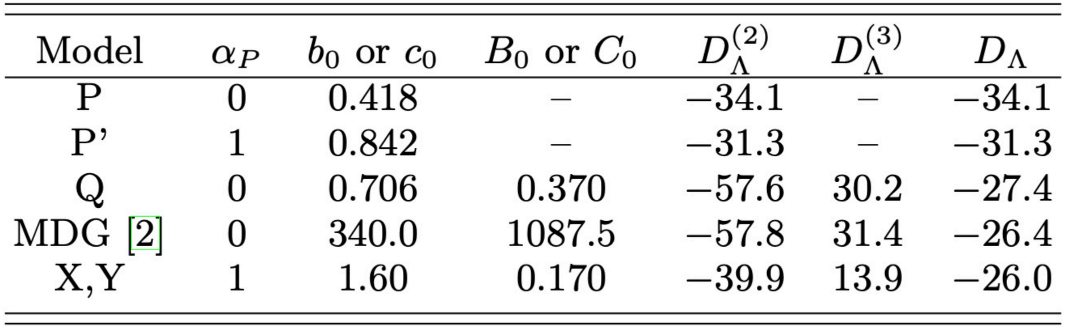
Constraints from Λ hypernuclei on the ΛNN content of the Λ-nucleus potential and the ‘hyperon puzzle’

E. Friedman[1] and A. Gal*[1]

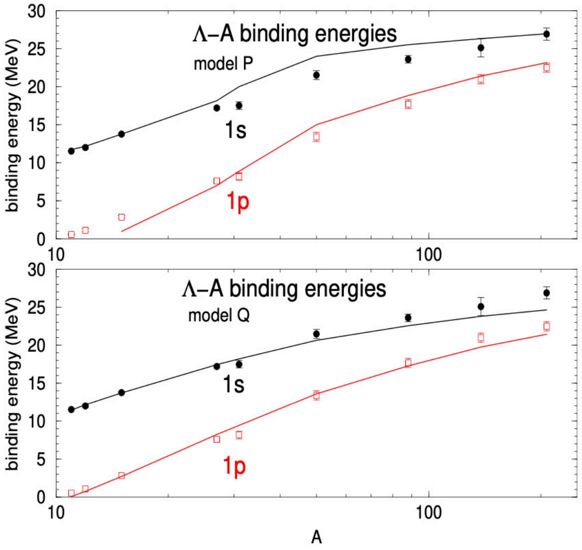
[1] Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

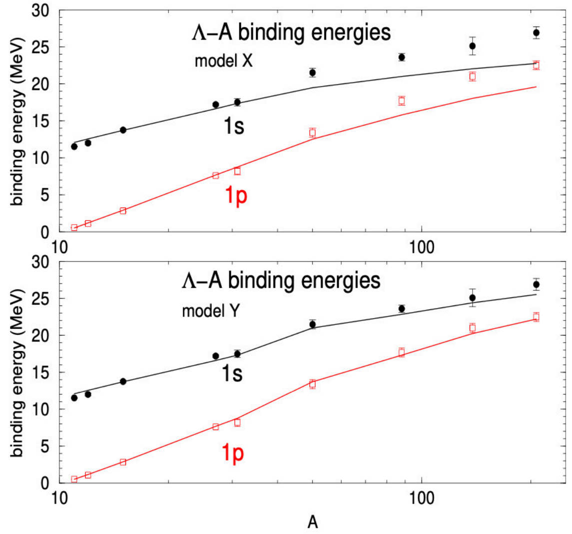
(Dated: April 12, 2022)

A depth of $D_\Lambda \approx -28$ MeV for the Λ-nucleus potential was confirmed in 1988 by studying Λ binding energies deduced from (π^+, K^+) spectra measured across the periodic table. Modern two-body hyperon-nucleon interaction models require additional interaction terms, most likely ΛNN three-body terms, to reproduce D_Λ. In this work we apply a suitably constructed Λ-nucleus density dependent optical potential to binding energy calculations of observed $1s_\Lambda$ and $1p_\Lambda$ states in the mass range $12 \leq A \leq 208$. The resulting ΛNN contribution to D_Λ, about 14 MeV repulsion at symmetric nuclear matter density $\rho_0 = 0.17$ fm^{-3}, has a potential to resolve the ‘hyperon puzzle’.



Model	α_P	b_0 or c_0	B_0 or C_0	$D^{(2)}_\Lambda$	$D^{(3)}_\Lambda$	D_Λ
P	0	0.418	–	−34.1	–	−34.1
P’	1	0.842	–	−31.3	–	−31.3
Q	0	0.706	0.370	−57.6	30.2	−27.4
MDG [2]	0	340.0	1087.5	−57.8	31.4	−26.4
X,Y	1	1.60	0.170	−39.9	13.9	−26.0





The moderate repulsión of ~ 14 MeV found is in good agreement with the work of Logoteta, I.V.& Bombaci mentioned before

(see Gal’s talk)

My personal feeling is that ….

- ✧ It is still an open question whether hyperonic TBFs can (only by themselves) be able to solve completely the hyperon puzzle or not
- ✧ It seems, however, that even if they are not the full solution, most probably they can contribute to it in a very important way

Solution III: Quark Matter Core

General Feature:

Some authors have suggested an early phase transition to deconfined quark matter as solution to the hyperon puzzle. Massive neutron stars could actually be hybrid stars with a stiff quark matter core.

To yield $M_{\max} > 2M_\odot$ Quark Matter should have:

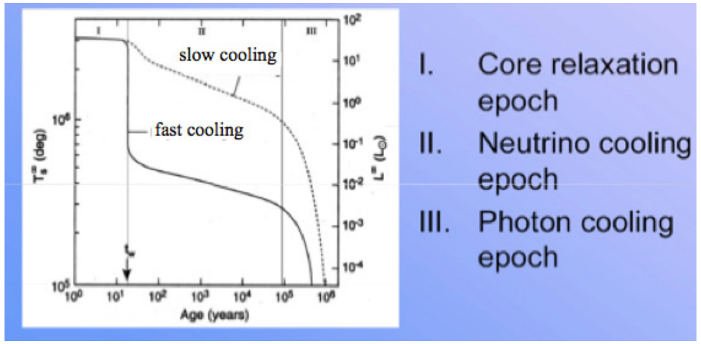
- significant overall quark repulsion → stiff EoS
- strong attraction in a channel → strong color superconductivity

Ozel et al., (2010), Weissenborn et al., (2011), Klaehn et al., (2011), Bonano & Sedrakian (2012), Lastowiecki et al., (2012), Zdunik & Haensel (2012)

Transport coefficients of hyperonic neutron star cores

Most of the effort have been concentrated on the role of hyperons in the EoS of NSs. However, NSs are **evolving objects** where various **dynamical processes** can occur. Their theoretical description requires **in addition to the EoS** the **knowledge of transport properties (e.g. thermal conductivity, shear viscosity) of dense NS matter** needed to understand NS cooling mechanism and/or their oscillation modes

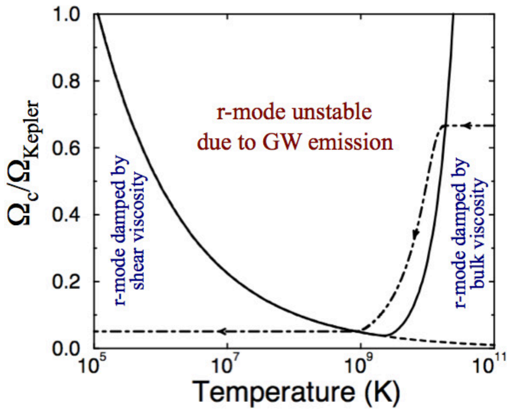
Cooling



- I. Core relaxation epoch
- II. Neutrino cooling epoch
- III. Photon cooling epoch

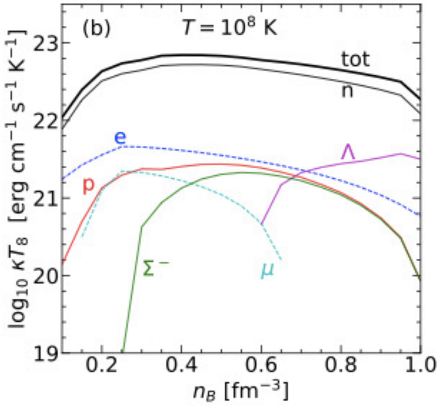
$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\gamma - L_\nu + H$$

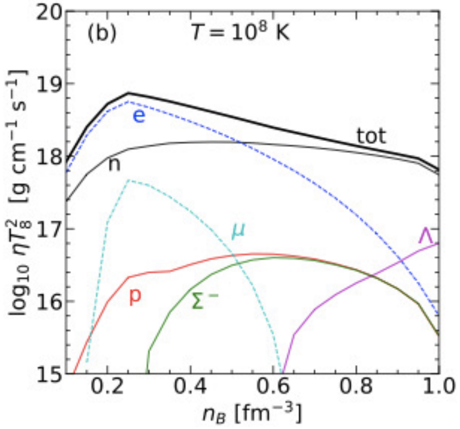
Oscillations due to undamped instabilities in rotation NS (r-modes)



$$\frac{1}{\tau(\Omega,T)} = -\frac{1}{\tau_{GW}(\Omega)} + \frac{1}{\tau_{Viscosity}(\Omega,T)} = 0$$

Recently, a study of transport properties (thermal conductivity, shear viscosity & momentum transfer rates) of non-superfluid npΣΛeμ β-stable matter has been done. The calculation is based on the transport theory of multicomponent Fermi liquids using as microscopic inputs (in-medium scattering matrices, NS composition & effective masses) obtained within the BHF approach employing the AV18 NN + UIX NNN forces plus the NSC97e YN & YY





✧ Neutrons dominate **the baryon contribution to the transport properties** as in the case of NS cores with only nucleons & **the total thermal conductivity** over the whole range of densities

✧ Although the p, Σ^- & Λ contributions are small, these species are **important in mediating the neutron mean free path**

✧ Due to the deleptonization of the NS core because of the appearance of Σ^-, neutrons dominate also **the shear viscosity at high densities** contrary to the case without hyperons where the lepton contribution dominates always this transport coefficient

Shternin & Vidaña, Universe 7, 203 (2021)

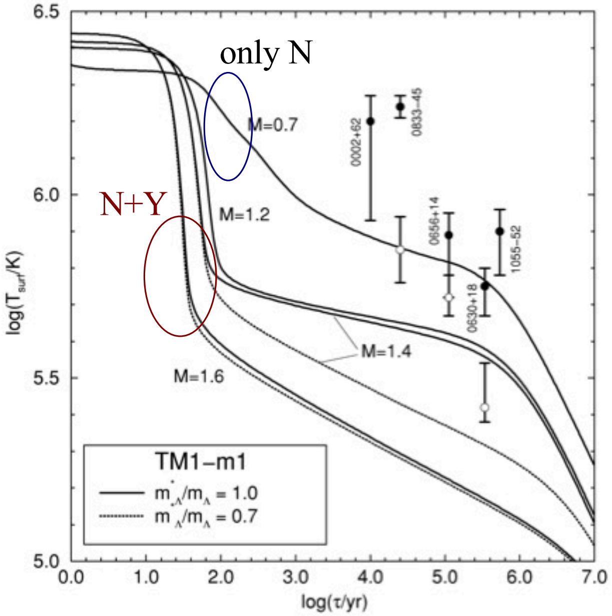
Hyperons & NS cooling

Hyperonic direct URCA processes are possible as soon as hyperons appear leading to additional fast cooling mechanisms

Process	R
$\Lambda \to p + l + \bar{\nu}_l$	0.0394
$\Sigma^- \to n + l + \bar{\nu}_l$	0.0125
$\Sigma^- \to \Lambda + l + \bar{\nu}_l$	0.2055
$\Sigma^- \to \Sigma^0 + l + \bar{\nu}_l$	0.6052
$\Xi^- \to \Lambda + l + \bar{\nu}_l$	0.0175
$\Xi^- \to \Sigma^0 + l + \bar{\nu}_l$	0.0282
$\Xi^0 \to \Sigma^+ + l + \bar{\nu}_l$	0.0564
$\Xi^- \to \Xi^0 + l + \bar{\nu}_l$	0.2218

+ partner reactions generating neutrinos,
Hyperonic MURCA, …

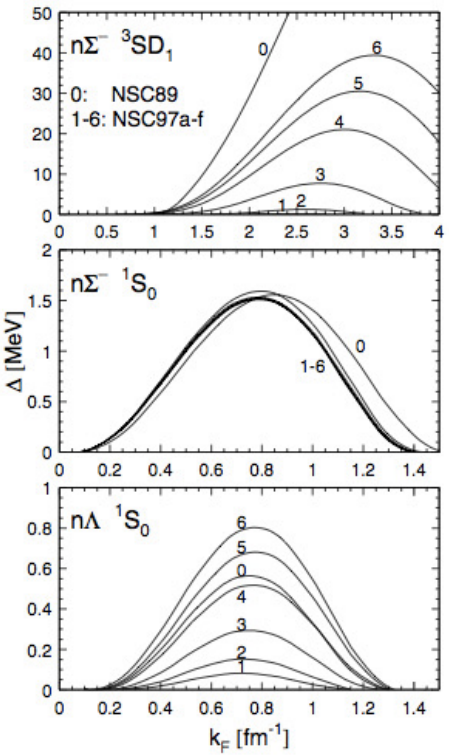
(Schaab, Shaffner-Bielich & Balberg 1998)



R: relative emissitivy w.r.t. nucleonic DURCA

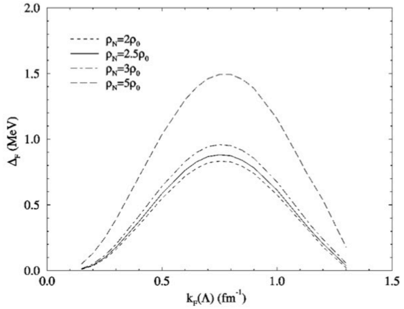
Pairing gaps are important for cooling calculations since they reduce specific heat & emissivities by an exponential factor $exp\left(-{}^{\Delta}/_{k_B T}\right)$

- $^1S_0$, $^3SD_1$ SN & $^1S_0$ ΛN gap

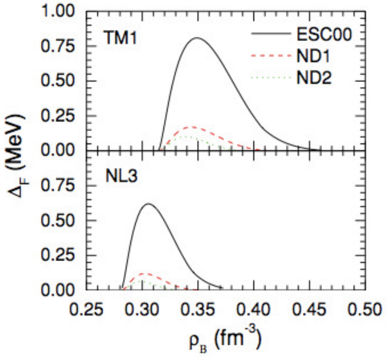


(Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0$ ΛΛ gap

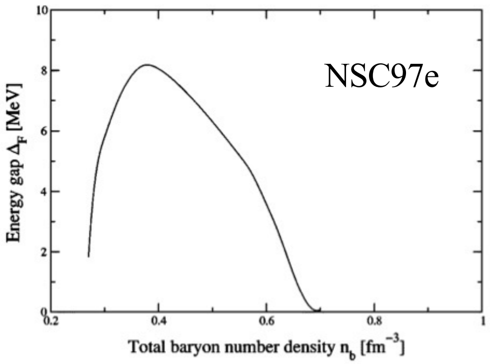


(Balberg & Barnea 1998)



(Wang & Shen 2010)

- $^1S_0$ ΣΣ gap



(I. V. & Tolós 2004)

The final message of this talk

We have briefly reviewed the role played by hyperons in neutron stars. Particularly, we have revised

- ✓ Hyperon puzzle & its possible solutions
  - It is still an open issue
  - Even if TBFs cannot be able to solve only by themselves completely the hyperon puzzle they contribute in a very important manner
- ✓ Transport coefficients in hyperonic on neutron star cores
- ✓ Role of hyperon on NS cooling
  - Hyperons lead to additional fast cooling mechanisms

- ✧ You for your time & attention
- ✧ The organizers for their kind invitation

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