Hyperonic Three-Body Forces & Consequences for Neutron Stars

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In this talk I will …

- Present NNΛ and NNΣ forces based on a two-meson exchange model

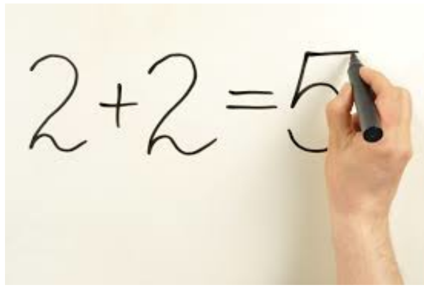
- Analyze the role of these forces in the solution of the hyperon puzzle

This study was part of the Ph.D. Thesis of Domenico Logoteta (University of Coimbra, September 2013)

Of course …

- ✧ He deserves all the credits

- ✧ I am the only responsible for any possible mistake



Hyperons in Neutron Stars

Hyperons in NS considered by many authors since the pioneering work of Ambartsumyan & Saakyan (1960)

Phenomenological approaches

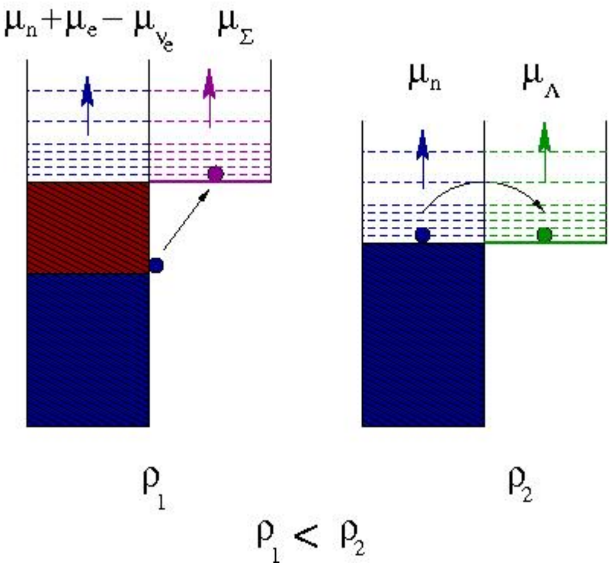
- ✧ Relativistic Mean Field Models: Glendenning 1985; Knorren et al. 1995; Shaffner-Bielich & Mishustin 1996, Bonano & Sedrakian 2012, …
- ✧ Non-realtivistic potential model: Balberg & Gal 1997
- ✧ Quark-meson coupling model: Pal et al. 1999, …
- ✧ Chiral Effective Lagrangians: Hanauske et al., 2000
- ✧ Density dependent hadron field models: Hofmann, Keil & Lenske 2001

Microscopic approaches

- ✧ Brueckner-Hartree-Fock theory: Baldo et al. 2000; I. V. et al. 2000, Schulze et al. 2006, I.V. et al. 2011, Burgio et al. 2011, Schulze & Rijken 2011
- ✧ DBHF: Sammarruca (2009), Katayama & Saito (2014)
- ✧ $V_{\text{low } k}$: Djapo, Schaefer & Wambach, 2010

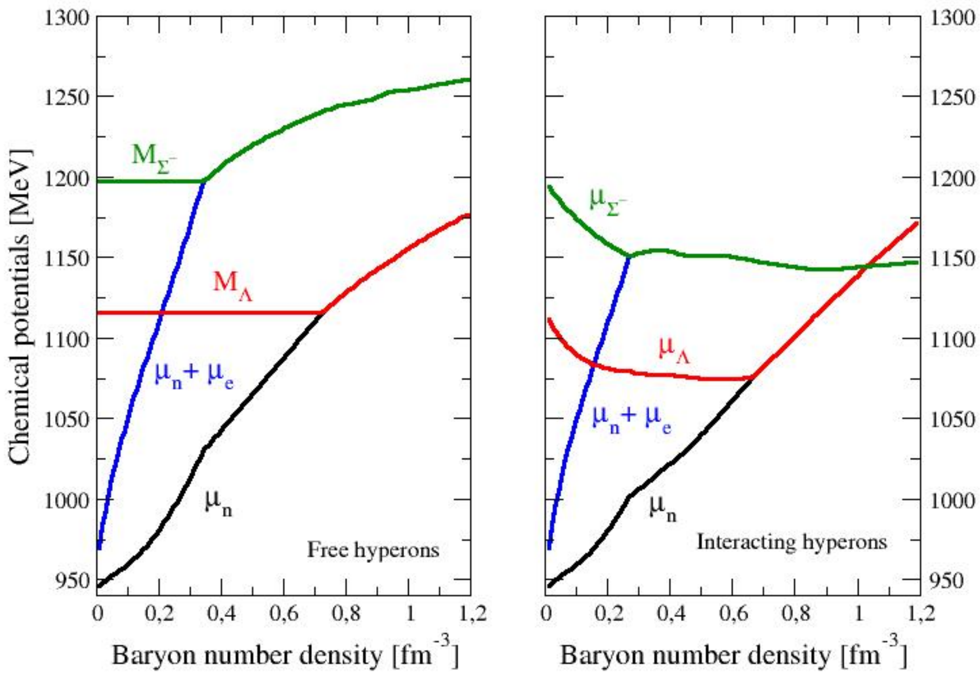
Sorry if I missed somebody

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.



$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-} - \mu_{\nu_{e^-}}$$

$$\mu_\Lambda = \mu_n$$



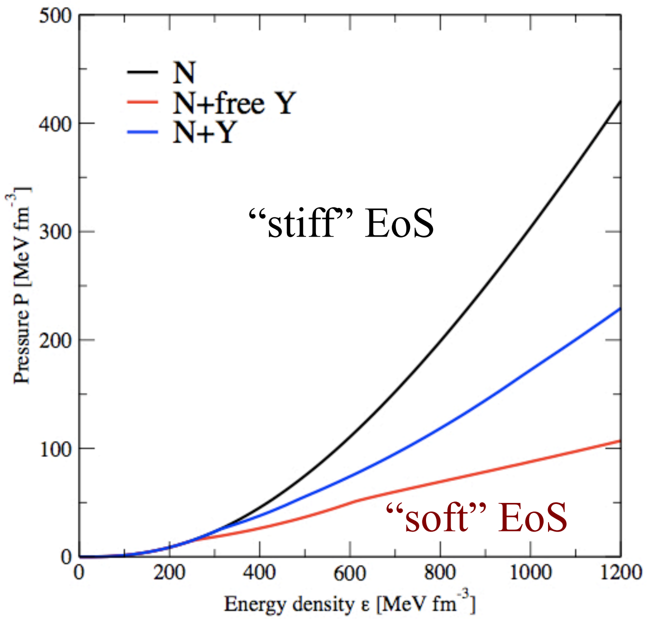
$$n + n \rightarrow n + \Lambda$$

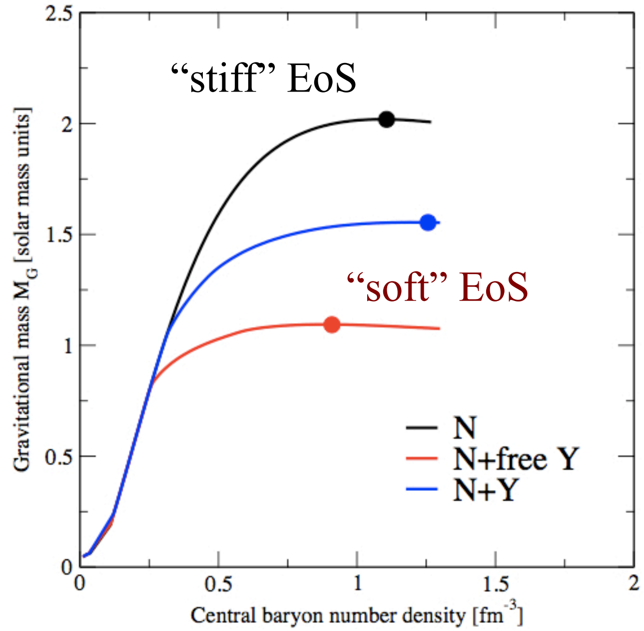
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

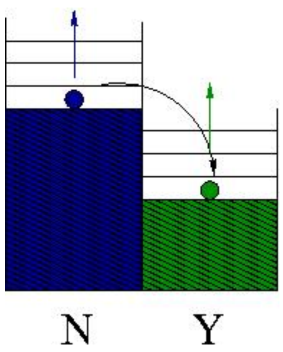
$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

Effect of Hyperons in the EoS and Mass of Neutron Stars



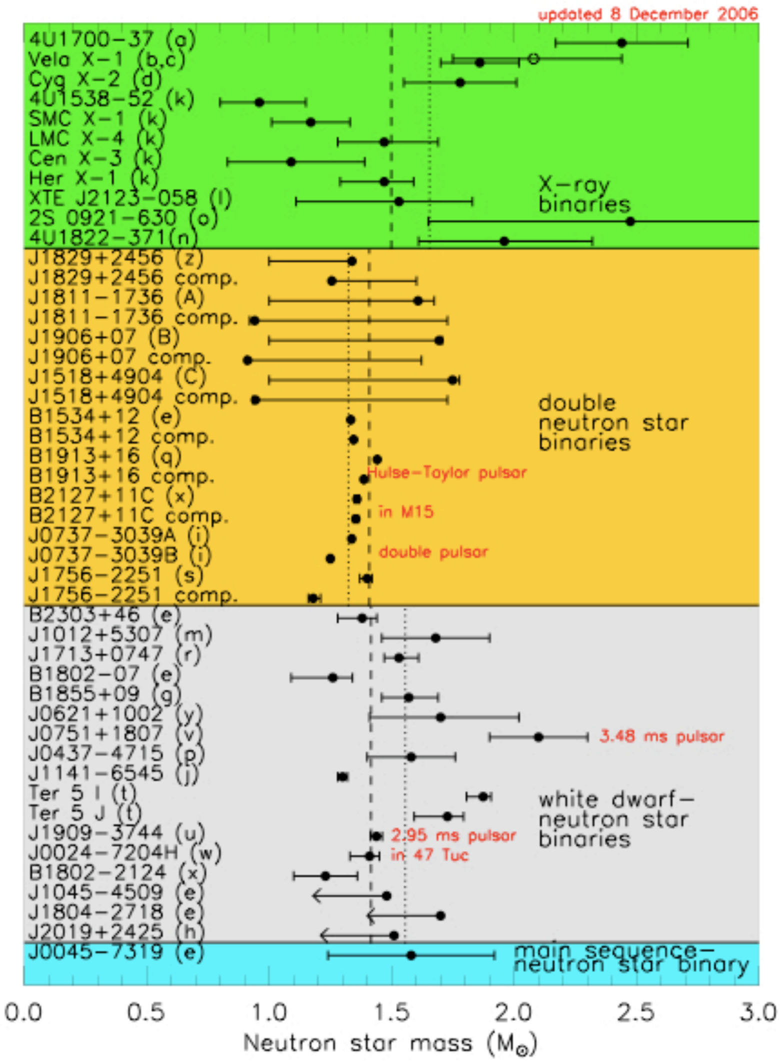




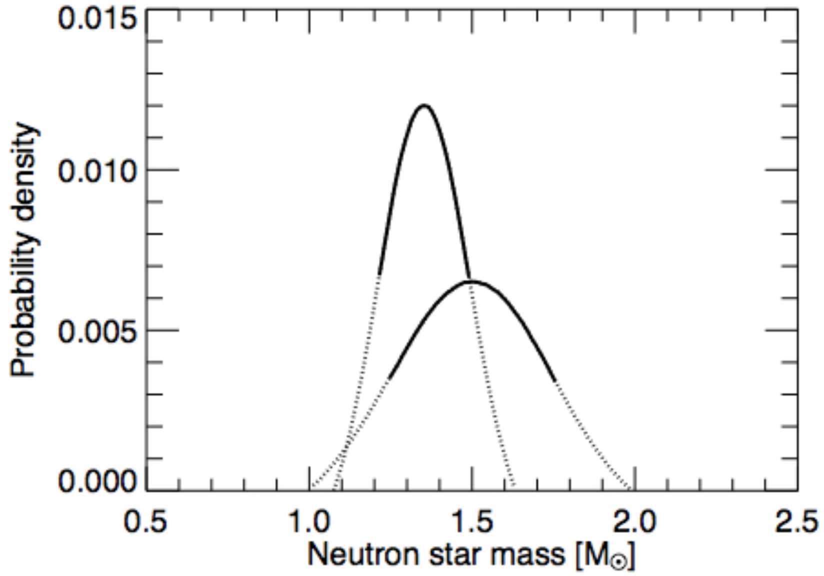
Relieve of Fermi pressure due to the appearance of hyperons ➔

EoS softer ➔ reduction of the mass

Measured Neutron Star Masses (up to ~ 2006-2008)



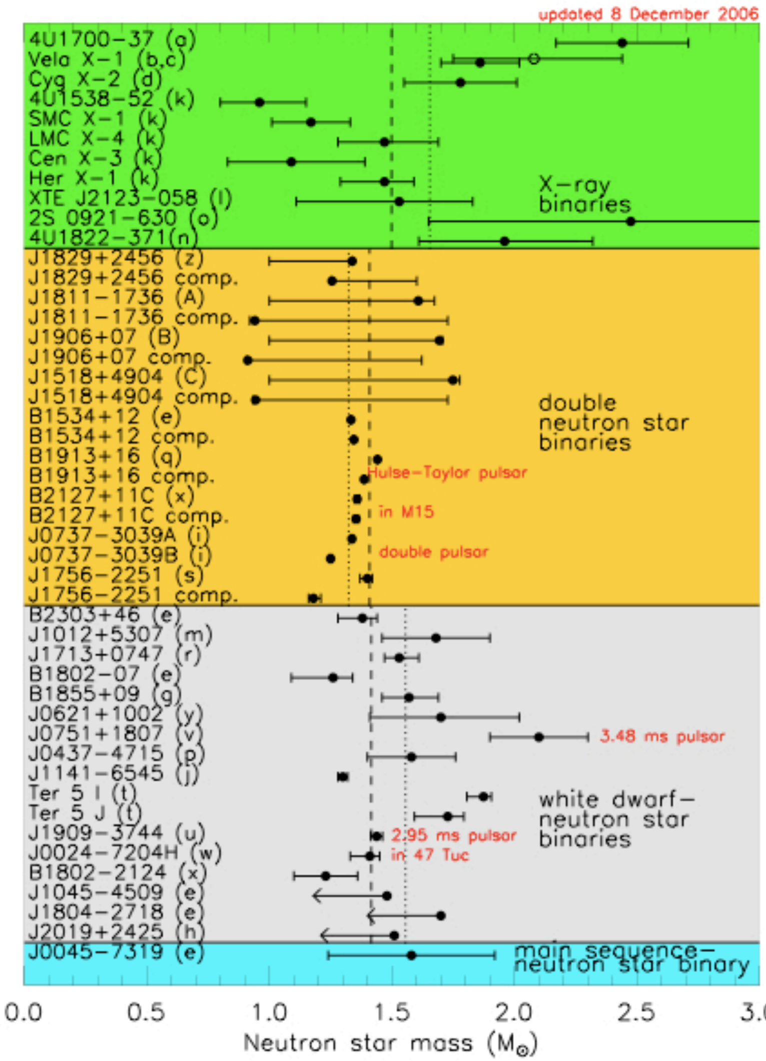
(Lattimer & Prakash 2007)



up to ~ 2006-2008 any valid EoS should predict

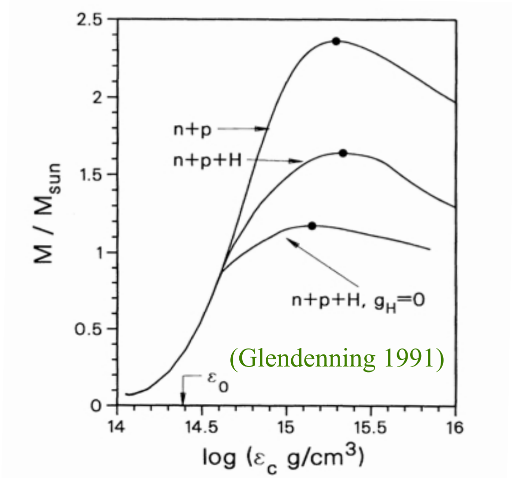
$$M_{\max}\left[EoS\right] > 1.4 - 1.5 M_{\odot}$$

Hyperons in NS
(up to ~ 2006-2008)



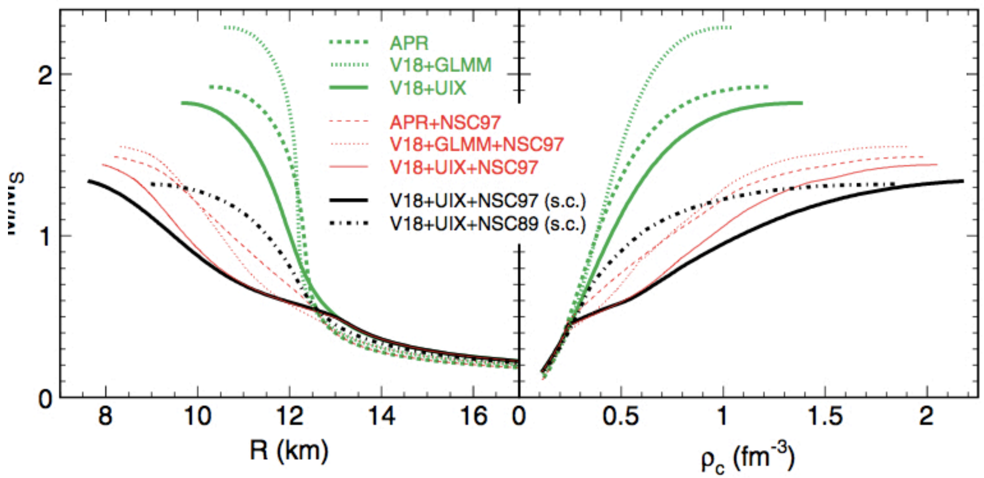
(Lattimer & Prakash 2007)

Phenomenological:
M_{max} compatible with 1.4-1.5 $M_\odot$



(Glendenning 1991)

Microscopic : M_{max} < 1.4-1.5 $M_\odot$



(Schulze, Polls, Ramos & IV 2006)

Recent measurements of high masses ⟶ life of hyperons more difficult

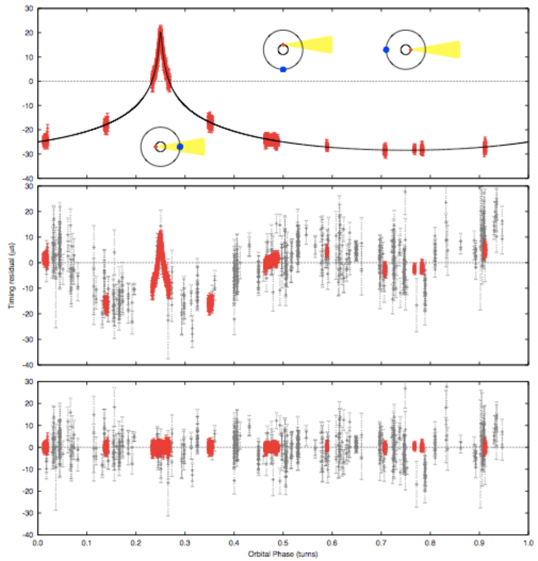
- PSR J164-2230 (Demorest et al. 2010)

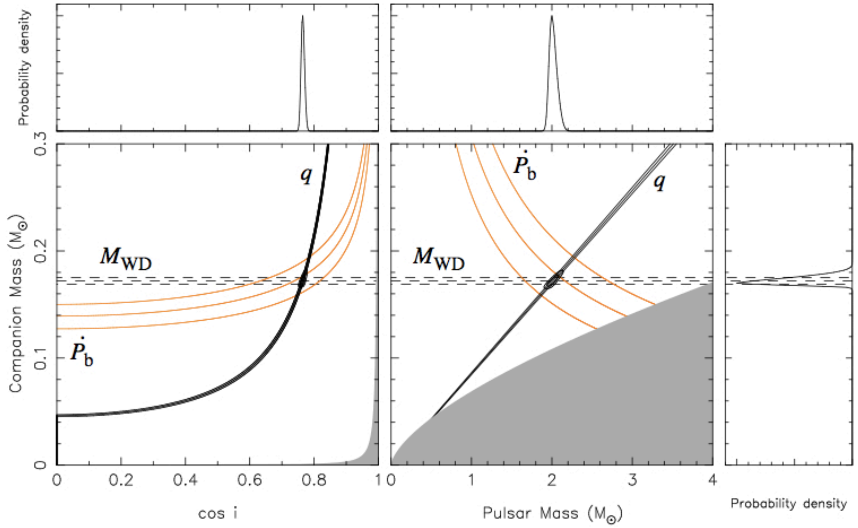
✓ binary system (P=8.68 d)

✓ low eccentricity ($\varepsilon=1.3 \times 10^{-6}$)

✓ companion mass: $\sim 0.5 M_{\odot}$

✓ pulsar mass: $M = 1.97 \pm 0.04 M_{\odot}$





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

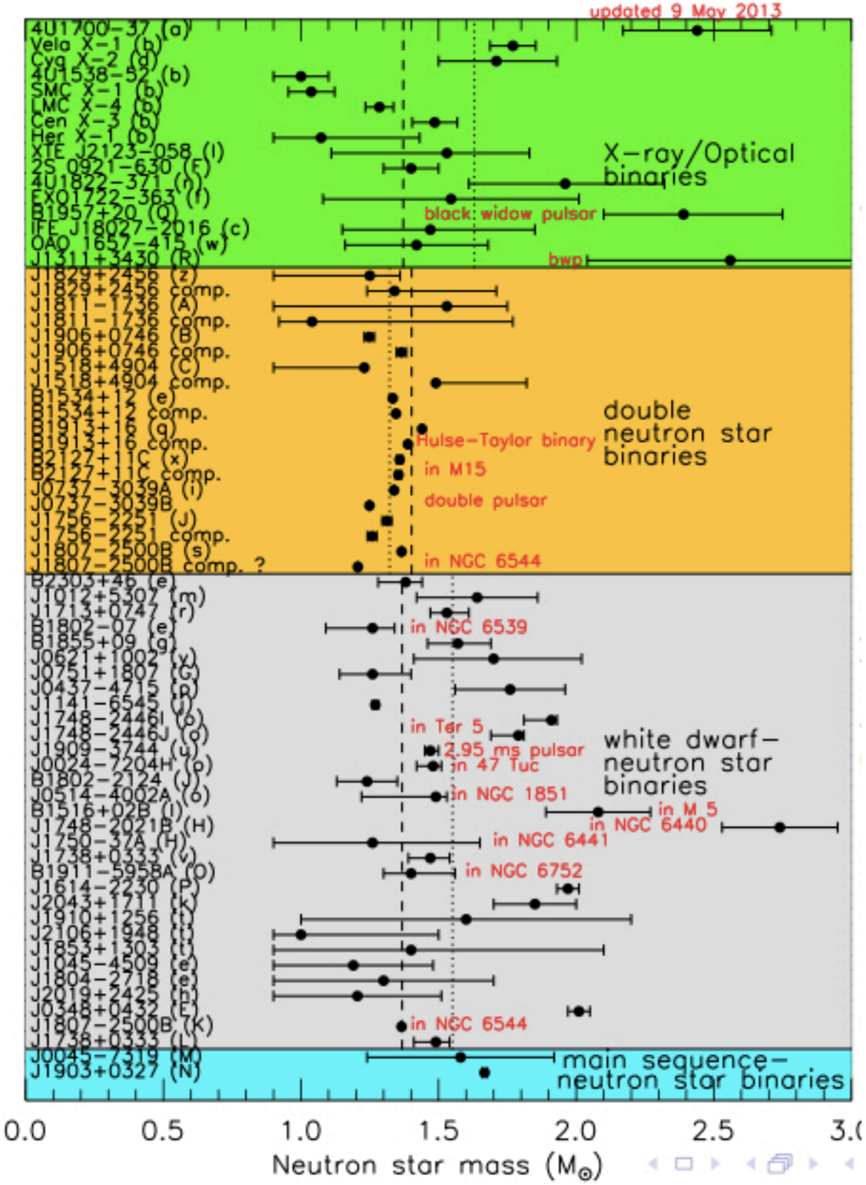
✓ binary system (P=2.46 h)

✓ very low eccentricity

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

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

Measured Neutron Star Masses (2015)



updated from Lattimer 2013

Observation of ~ 2 M_{sun} neutron stars

↓

Dense matter EoS stiff enough is required such that

$$M_{\max}\left[EoS\right] > 2M_{\odot}$$

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

The Hyperon Puzzle

"Hyperons → "soft (or too soft) EoS" not compatible (mainly in microscopic approaches) with measured (high) masses. However, the presence of hyperons in the NS interior seems to be unavoidable."

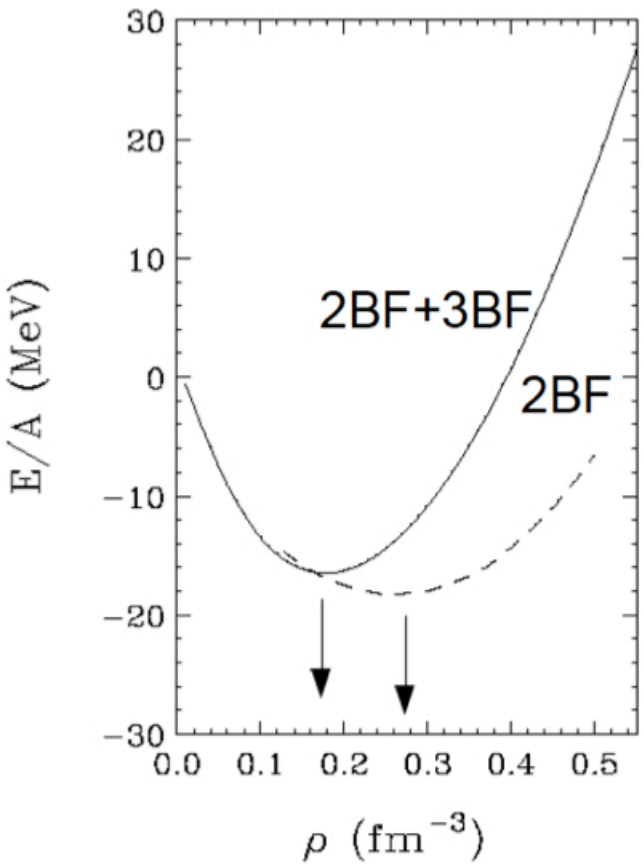
- ✓ can YN & YY interactions still solve it ?
- ✓ or perhaps hyperonic three-body forces ?
- ✓ what about quark matter ?

Can Hyperonic TBF solve this puzzle ?

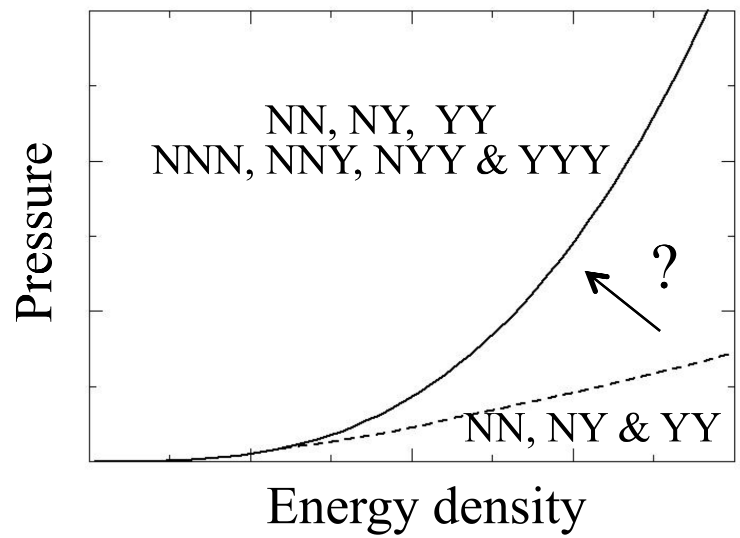
Natural solution based on: Importance of NNN force in Nuclear Physics

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

NNN Force

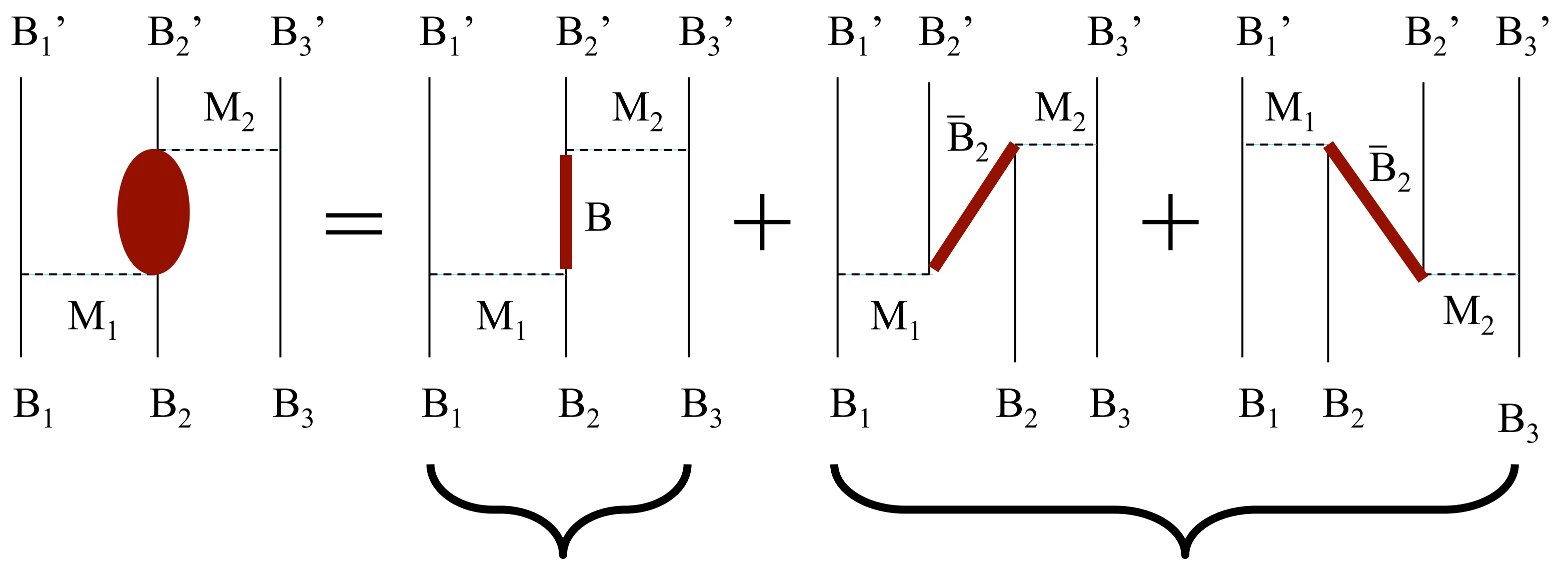


NNY, NYY & YYY Forces



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

Two-meson exchange Hyperonic TBF



B_i B_i': N, Λ, Σ

B - excitation

Z – diagram

M_i: π, K, σ, ω

B: Λ, Σ, Δ, Σ*

$\bar{B}_2$: $\bar{N}$, $\bar{\Lambda}$, $\bar{\Sigma}$

Vertices: consistent with YN and YY

Repulsion at high densities due to Z-diagram as in NNN

Baryon-excitation contribution
(π-, K-exchange)

$$V^{M_1M_2,R}_{NNY\leftrightarrow NNY'} = C^{M_1M_2,R}_{NNY\leftrightarrow NNY'}\left(\hat{O}_I\left\{X_{12}(\vec{r}_{12}),X_{23}(\vec{r}_{23})\right\}\right.$$
$$\left.+\hat{O}_{II}\left[X_{12}(\vec{r}_{12}),X_{23}(\vec{r}_{23})\right]\right)$$

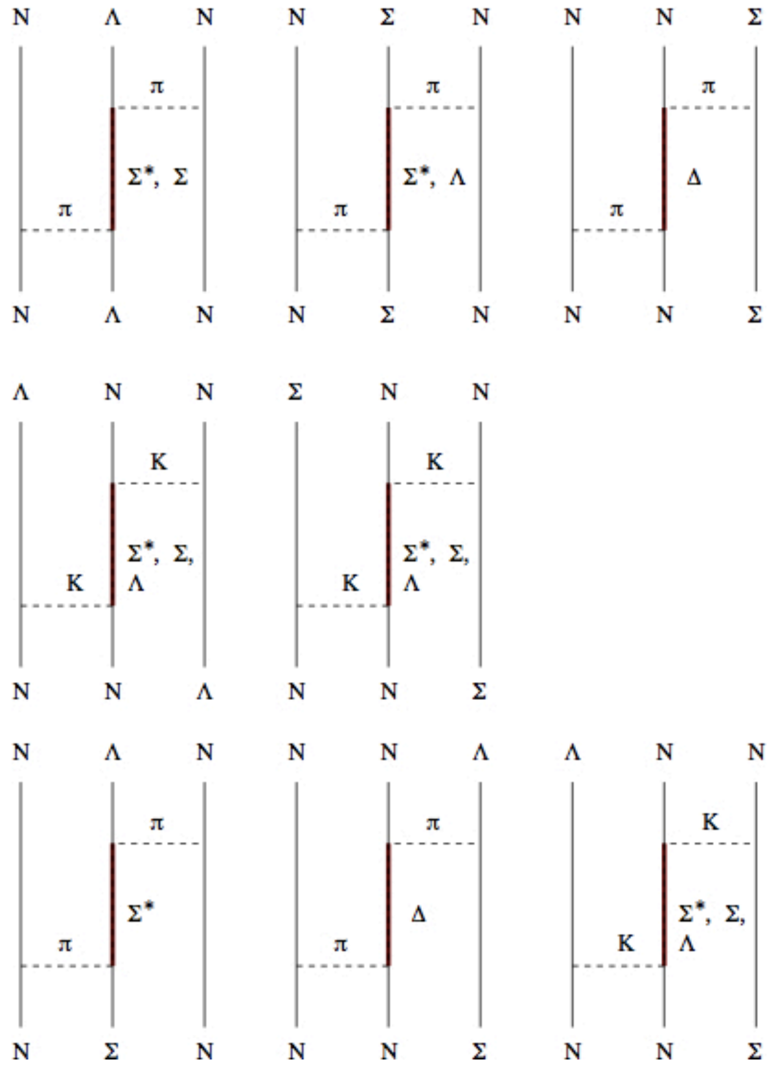
$\hat{O}_I,\hat{O}_{II} \rightarrow$ isospin structure

$$X_{ij}(\vec{x}) = \vec{\sigma}_i\cdot\vec{\sigma}_j Y_{ij}(x) + \hat{S}_{ij}(\hat{x})T_{ij}(x)$$

$$Y_{ij}(x) = \frac{\partial^2 Z_{ij}}{\partial x^2} + \frac{2}{x}\frac{\partial Z_{ij}}{\partial x},\quad T_{ij}(x) = \frac{\partial^2 Z_{ij}}{\partial x^2} - \frac{1}{x}\frac{\partial Z_{ij}}{\partial x}$$

$$Z_{12}(x) = \frac{4\pi}{m_{M_1}}\int\frac{d\vec{k}}{(2\pi)^3}\frac{e^{-i\vec{k}\cdot\vec{x}}}{k^2+m^2_{M_1}}F_{B_1B_1'M_1}(k^2)F_{B_2BM_1}(k^2)$$

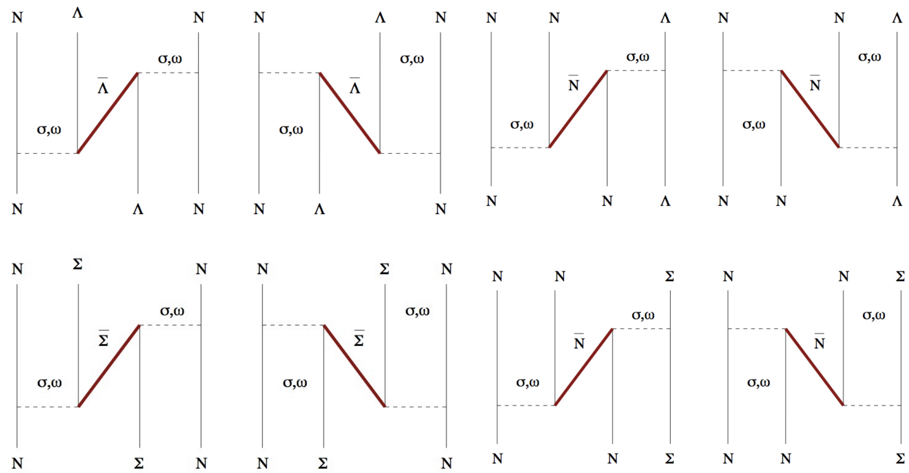
$$Z_{23}(x) = \frac{4\pi}{m_{M_2}}\int\frac{d\vec{q}}{(2\pi)^3}\frac{e^{-i\vec{k}\cdot\vec{x}}}{q^2+m^2_{M_2}}F_{B_3B_3'M_2}(q^2)F_{B_2'BM_2}(q^2)$$



Numerical factors & Isospin structure

Process	$M_1 M_2$	R	$C^{M_1 M_2, R}_{NNY \leftrightarrow NNY'}$	$\hat{O}_I$	$\hat{O}_{II}$
$NN\Lambda \leftrightarrow NN\Lambda$	$\pi\pi$	Σ	$\frac{1}{9}\frac{\tilde{f}^2_{NN\pi}\tilde{f}^2_{\Lambda\Sigma\pi}}{16\pi^2}\frac{m_\pi^2}{m_\Sigma - m_\Lambda}$	$\vec{\tau}_1 \cdot \vec{\tau}_3$	–
	$\pi\pi$	Σ^*	$-\frac{2}{27}\frac{\tilde{f}^2_{NN\pi}f^2_{\Lambda\Sigma^*\pi}}{16\pi^2}\frac{m_\pi^2}{m_{\Sigma^*} - m_\Lambda}$	$\vec{\tau}_1 \cdot \vec{\tau}_3$	–
	KK	Λ	$-\frac{1}{9}\frac{\tilde{f}^4_{N\Lambda K}}{16\pi^2}\frac{m_K^2}{m_N - m_\Lambda}\frac{m_K^4}{m_\pi^4}$	1	-
	KK	Σ	$-\frac{1}{18}\frac{\tilde{f}^2_{N\Lambda K}\tilde{f}^2_{N\Sigma K}}{16\pi^2}\frac{m_K^2}{m_N - m_\Sigma}\frac{m_K^4}{m_\pi^4}$	$\left\{\vec{I}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{I}_3\right\}$	$\left[\vec{I}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{I}_3\right]$
	KK	Σ^*	$-\frac{1}{27}\frac{\tilde{f}^2_{N\Lambda K}f^2_{N\Sigma^* K}}{16\pi^2}\frac{m_K^2}{m_{\Sigma^*} - m_N}\frac{m_K^4}{m_\pi^4}$	$\left\{\vec{I}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{I}_3\right\}$	$-\frac{1}{2}\left[\vec{I}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{I}_3\right]$
$NN\Sigma \leftrightarrow NN\Sigma$	$\pi\pi$	Λ	$-\frac{1}{9}\frac{\tilde{f}^2_{NN\pi}\tilde{f}^2_{\Lambda\Sigma\pi}}{16\pi^2}\frac{m_\pi^2}{m_\Sigma - m_\Lambda}$	$\vec{\tau}_1 \cdot \vec{\tau}_3$	–
	$\pi\pi$	Δ	$-\frac{2}{81}\frac{\tilde{f}^2_{N\Sigma\pi}f^2_{N\Delta\pi}}{16\pi^2}\frac{m_\pi^2}{m_\Delta - m_N}$	$\left\{\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{I}_3\right\}$	$\frac{1}{4}\left[\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{I}_3\right]$
	$\pi\pi$	Σ^*	$-\frac{2}{27}\frac{\tilde{f}^2_{NN\pi}f^2_{\Sigma\Sigma^*\pi}}{16\pi^2}\frac{m_\pi^2}{m_{\Sigma^*} - m_\Sigma}$	$\vec{\tau}_1 \cdot \vec{\tau}_3$	–
	KK	Λ	$-\frac{1}{9}\frac{\tilde{f}^2_{N\Lambda K}\tilde{f}^2_{N\Sigma K}}{16\pi^2}\frac{m_K^2}{m_N - m_\Lambda}\frac{m_K^4}{m_\pi^4}$	$\vec{\tau}_1 \cdot \vec{\tau}_3$	–
	KK	Σ	$-\frac{1}{18}\frac{\tilde{f}^4_{N\Sigma K}}{16\pi^2}\frac{m_K^2}{m_N - m_\Sigma}\frac{m_K^4}{m_\pi^4}$	$\left\{\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right\}$	$\left[\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right]$
	KK	Σ^*	$-\frac{1}{27}\frac{\tilde{f}^2_{N\Sigma K}f^2_{N\Sigma^* K}}{16\pi^2}\frac{m_K^2}{m_{\Sigma^*} - m_N}\frac{m_K^4}{m_\pi^4}$	$\left\{\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right\}$	$-\frac{1}{2}\left[\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right]$
$NN\Sigma \leftrightarrow NN\Lambda$	$\pi\pi$	Σ^*	$-\frac{2}{27}\frac{\tilde{f}^2_{NN\pi}f_{\Lambda\Sigma^*\pi}f_{\Sigma\Sigma^*\pi}}{16\pi^2}\frac{m_\pi^2}{(m_{\Sigma^*} - (m_\Sigma + m_\Lambda)/2)}$	$(\vec{\tau}_1 \cdot \vec{I}_2)(\vec{\rho}_2 \cdot \vec{\tau}_3)$	–
	$\pi\pi$	Δ	$-\frac{2}{81}\frac{\tilde{f}_{NN\pi}\tilde{f}_{\Lambda\Sigma\pi}f^2_{N\Delta\pi}}{16\pi^2}\frac{m_\pi^2}{m_\Delta - m_N}$	$\left\{\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\rho}_3\right\}$	$\frac{1}{4}\left[\vec{\tau}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\rho}_3\right]$
	KK	Λ	$-\frac{1}{9}\frac{\tilde{f}^3_{N\Lambda K}\tilde{f}_{N\Sigma K}}{16\pi^2}\frac{m_K^2}{m_N - m_\Lambda}\frac{m_K^4}{m_\pi^4}$	$\vec{\rho}_1 \cdot \vec{\tau}_3$	–
	KK	Σ	$-\frac{1}{18}\frac{\tilde{f}^3_{N\Sigma K}\tilde{f}_{N\Lambda K}}{16\pi^2}\frac{m_K^2}{m_N - m_\Sigma}\frac{m_K^4}{m_\pi^4}$	$\left\{\vec{\rho}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right\}$	$\left[\vec{\rho}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right]$
	KK	Σ^*	$-\frac{1}{27}\frac{\tilde{f}^3_{N\Sigma K}\tilde{f}^2_{N\Lambda K}}{16\pi^2}\frac{m_K^2}{m_{\Sigma^*} - m_N}\frac{m_K^4}{m_\pi^4}$	$\left\{\vec{\rho}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right\}$	$-\frac{1}{2}\left[\vec{\rho}_1 \cdot \vec{\tau}_2, \vec{\tau}_2 \cdot \vec{\tau}_3\right]$

Z-diagram contribution (σ,ω-exchange)



- σσ–exchange contribution

$$V_{NNY}^{\sigma\sigma,\bar{B}} = C_{NNY}^{\sigma\sigma,\bar{B}}\Big(-4Z_{12}(r_{12})Z_{23}(r_{23})\nabla^2_{r_2'} - 4Z_{12}'(r_{12})Z_{23}(r_{23})\hat{r}_{12}\cdot\nabla_{r_2'}$$

$$-4Z_{12}(r_{12})Z_{23}'(r_{23})\hat{r}_{23}\cdot\nabla_{r_2'} - \big(Y_{12}(r_{12})Z_{23}(r_{23})+Z_{12}(r_{12})Y_{23}(r_{23})\big)$$

$$-\hat{r}_{12}\cdot\hat{r}_{23}Z_{12}'(r_{12})Z_{23}'(r_{23}) - 2i\big(Z_{12}'(r_{12})Z_{23}(r_{23})\vec{\sigma}_2\cdot\hat{r}_{12}\times\nabla_{r_2'}$$

$$+Z_{12}(r_{12})Z_{23}'(r_{23})\vec{\sigma}_2\cdot\hat{r}_{23}\times\nabla_{r_2'}\big)\Big)\delta(\vec{r}_1-\vec{r}_1')\delta(\vec{r}_2-\vec{r}_2')\delta(\vec{r}_3-\vec{r}_3')$$

- ## ωω–exchange contribution

$$
\begin{aligned}
V_{NNY}^{\omega\omega,\bar{B}} = C_{NNY}^{\omega\omega,\bar{B}} \Big(\Big(\big(1+\vec{\sigma}_1\cdot\vec{\sigma}_2+\vec{\sigma}_1\cdot\vec{\sigma}_2+\vec{\sigma}_2\cdot\vec{\sigma}_3\big)\hat{r}_{12}\cdot\hat{r}_{23}-\vec{\sigma}_1\cdot\hat{r}_{23}\vec{\sigma}_2\cdot\hat{r}_{12}-\vec{\sigma}_2\cdot\hat{r}_{23}\vec{\sigma}_3\cdot\hat{r}_{12} \\
-\vec{\sigma}_1\cdot\hat{r}_{23}\vec{\sigma}_3\cdot\hat{r}_{12}\Big) Z_{12}^{'}(r_{12})Z_{23}^{'}(r_{23})-2iZ_{12}^{'}(r_{12})Z_{23}(r_{23})\big(\vec{\sigma}_2+\vec{\sigma}_3\big)\cdot\hat{r}_{12}\times\nabla_{r_3^{'}} \\
-2iZ_{12}(r_{12})Z_{23}^{'}(r_{23})\big(\vec{\sigma}_2+\vec{\sigma}_3\big)\cdot\hat{r}_{23}\times\nabla_{r_2^{'}}-4Z_{12}(r_{12})Z_{23}(r_{23})\nabla_{r_1^{'}}\cdot\nabla_{r_3^{'}}\Big) \\
\delta\big(\vec{r}_1-\vec{r}_1^{\,'}\big)\delta\big(\vec{r}_2-\vec{r}_2^{\,'}\big)\delta\big(\vec{r}_3-\vec{r}_3^{\,'}\big)
\end{aligned}
$$

- ## σω–exchange contribution

$$
\begin{aligned}
V_{NNY}^{\sigma\omega,\bar{B}} = C_{NNY}^{\sigma\omega,\bar{B}} \Big(\Big(\big(1+\vec{\sigma}_2\cdot\vec{\sigma}_3\big)Z_{12}(r_{12})Y_{23}(r_{23})-2iZ_{12}(r_{12})Z_{23}^{'}(r_{23})\big(\vec{\sigma}_2+\vec{\sigma}_3\big)\cdot\hat{r}_{23}\times\nabla_{r_2^{'}} \\
+2iZ_{12}^{'}(r_{12})Z_{23}^{'}(r_{23})\big(\vec{\sigma}_2+\vec{\sigma}_3\big)\cdot\hat{r}_{12}\times\hat{r}_{23}+2iZ_{12}(r_{12})Z_{23}^{'}(r_{23})\vec{\sigma}_2\cdot\hat{r}_{23}\times\nabla_{r_3^{'}} \\
+2Z_{12}^{'}(r_{12})Z_{23}(r_{23})\hat{r}_{12}\cdot\nabla_{r_3^{'}}+2Z_{12}(r_{12})Z_{23}^{'}(r_{23})\hat{r}_{23}\cdot\nabla_{r_3^{'}}+4Z_{12}(r_{12})Z_{23}(r_{23})\nabla_{r_2^{'}}\cdot\nabla_{r_3^{'}} \\
-\frac{1}{3}\Big(\vec{\sigma}_2\cdot\vec{\sigma}_3Y_{12}(r_{12})+\hat{S}_{23}(\hat{r}_{23})T_{23}(r_{23})\Big)Z_{12}(r_{12})\Big) \\
+D_{NNY}^{\sigma\omega,\bar{B}}\Big(-Y_{12}(r_{12})+Y_{23}(r_{23})-4Z_{12}^{'}(r_{12})Z_{23}^{'}(r_{23})-3Z_{12}^{'}(r_{12})\nabla_{r_2^{'}}\cdot\hat{r}_{12}\Big) \\
+i\vec{\sigma}_2\cdot\Big(2\nabla_{r_{23}}\times\nabla_{r_{12}}-5\nabla_{r_2^{'}}\times\hat{r}_{23}\Big)Z_{12}(r_{12})Z_{23}(r_{23}) \\
+\Big(\vec{r}_{12}\leftrightarrow\vec{r}_{23},\vec{r}_1\leftrightarrow\vec{r}_1^{\,'},\vec{r}_2\leftrightarrow\vec{r}_2^{\,'},\vec{\sigma}_1\leftrightarrow\vec{\sigma}_3\Big)\Big)\delta(\vec{r}_1-\vec{r}_1^{\,'})\delta(\vec{r}_2-\vec{r}_2^{\,'})\delta(\vec{r}_3-\vec{r}_3^{\,'})
\end{aligned}
$$

But that's only the beginning of the full story

there are

MANY, MANY, MANY more forces & contributions ….

Domenico in 2010

Domenico in 2013

BHF approximation of Hyperonic Matter

✧ Energy per particle

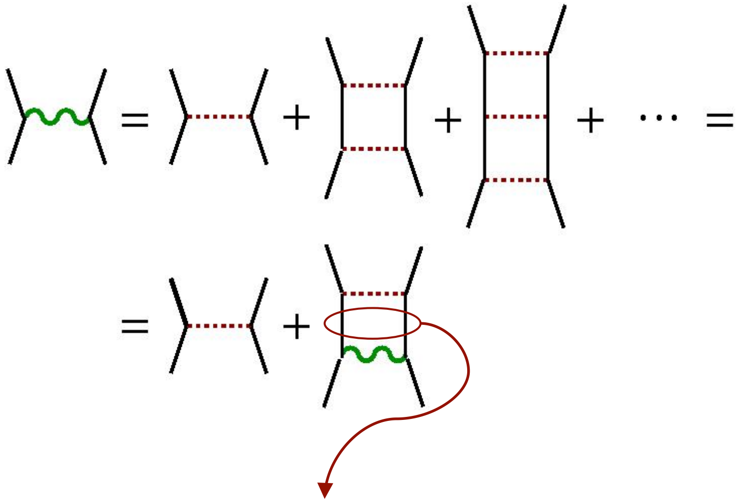
- $$\frac{E}{A}(\rho,\beta)=\frac{1}{A}\sum_{B}\sum_{k\le k_{F_B}}\left(\frac{\hbar^2k^2}{2m_B}+\frac{1}{2}\mathrm{Re}\left[U_B(\vec{k})\right]\right)$$

Infinite sumation of two-hole line diagrams

✧ Bethe-Goldstone Equation

Partial sumation of pp ladder diagrams

- $$G(\omega)=V+V\frac{Q}{\omega-E-E^{'}+i\eta}G(\omega)$$
- $$E_B(k)=\frac{\hbar^2k^2}{2m_B}+\mathrm{Re}\left[U_N(k)\right]+m_B$$
- $$U_B(k)=\sum_{B'}\sum_{k'\le k_{F_{B'}}}\left\langle \vec{k}\vec{k}'\right|G\left(\omega=E_B(k)+E_{B'}(k')\right)\left|\vec{k}\vec{k}'\right\rangle$$



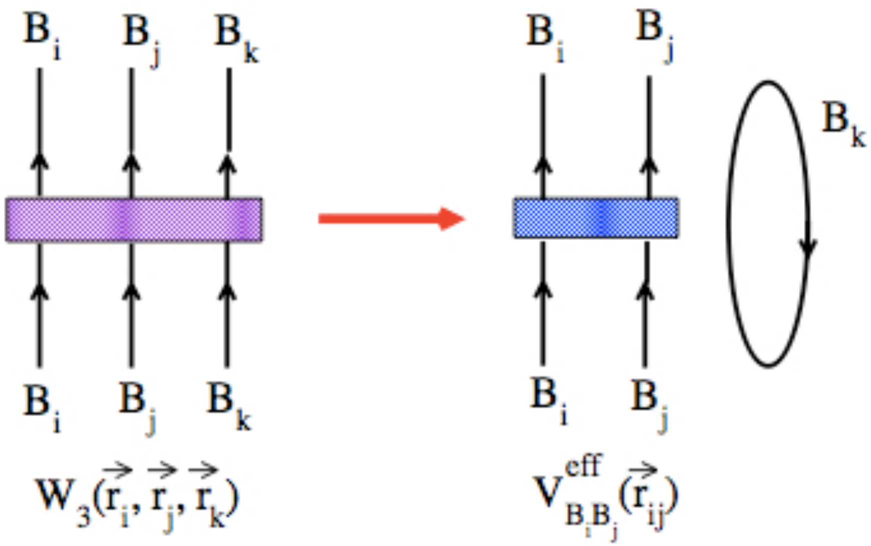
- ✓ Pauli blocking
- ✓ Baryon dressing

✧ Coupled Channels

	S = 0	S = -1	S = -2	S = -3	S = -4
I = 0	$(NN \rightarrow NN)$		$\begin{pmatrix} \Lambda\Lambda \rightarrow \Lambda\Lambda & \Lambda\Lambda \rightarrow \Xi N & \Lambda\Lambda \rightarrow \Sigma\Sigma \\ \Xi N \rightarrow \Lambda\Lambda & \Xi N \rightarrow \Xi N & \Xi N \rightarrow \Sigma\Sigma \\ \Sigma\Sigma \rightarrow \Lambda\Lambda & \Sigma\Sigma \rightarrow \Xi N & \Sigma\Sigma \rightarrow \Sigma\Sigma \end{pmatrix}$		$(\Xi\Xi \rightarrow \Xi\Xi)$
I = 1/2		$\begin{pmatrix} \Lambda N \rightarrow \Lambda N & \Lambda N \rightarrow \Sigma N \\ \Sigma N \rightarrow \Lambda N & \Sigma N \rightarrow \Sigma N \end{pmatrix}$		$\begin{pmatrix} \Lambda\Xi \rightarrow \Lambda\Xi & \Lambda\Xi \rightarrow \Sigma\Xi \\ \Sigma\Xi \rightarrow \Lambda\Xi & \Sigma\Xi \rightarrow \Sigma\Xi \end{pmatrix}$	
I = 1	$(NN \rightarrow NN)$		$\begin{pmatrix} \Xi N \rightarrow \Xi N & \Xi N \rightarrow \Lambda\Sigma & \Xi N \rightarrow \Sigma\Sigma \\ \Lambda\Sigma \rightarrow \Xi N & \Lambda\Sigma \rightarrow \Lambda\Sigma & \Lambda\Sigma \rightarrow \Sigma\Sigma \\ \Sigma\Sigma \rightarrow \Xi N & \Sigma\Sigma \rightarrow \Lambda\Sigma & \Sigma\Sigma \rightarrow \Sigma\Sigma \end{pmatrix}$		$(\Xi\Xi \rightarrow \Xi\Xi)$
I = 3/2		$(\Sigma N \rightarrow \Sigma N)$		$(\Sigma\Xi \rightarrow \Sigma\Xi)$	
I = 2			$(\Sigma\Sigma \rightarrow \Sigma\Sigma)$		

Three-Body Forces within the BHF approach

TBF can be introduced in our BHF approach by adding effective density-dependent two body forces to the baryon-baryon interactions V when solving the Bethe-Goldstone equation

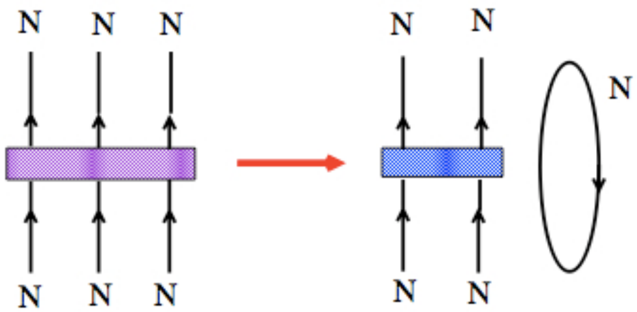


$$V^{eff}_{B_iB_j}\left(\vec{r}_{ij}\right) = \int W_3\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right) n\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right) d^3\vec{r}_k$$

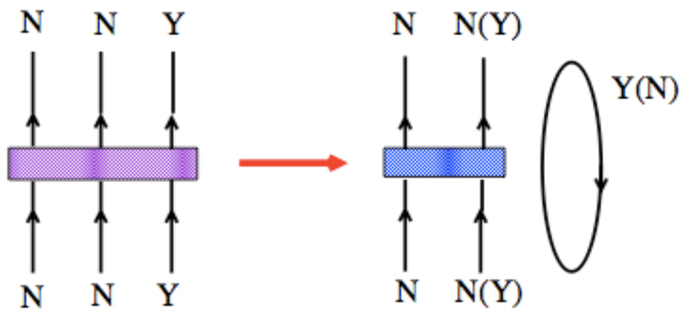
$W_3\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right)$: genuine TBF $\qquad$ $n\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right)$: three-body correlation function

From the genuine NNN,NNY, NYY and YYY TBF …

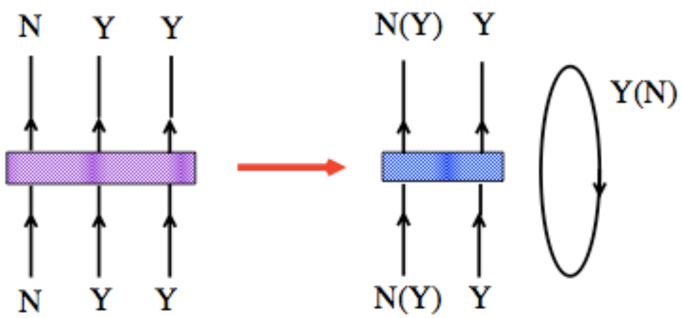
NNN ➔ NN



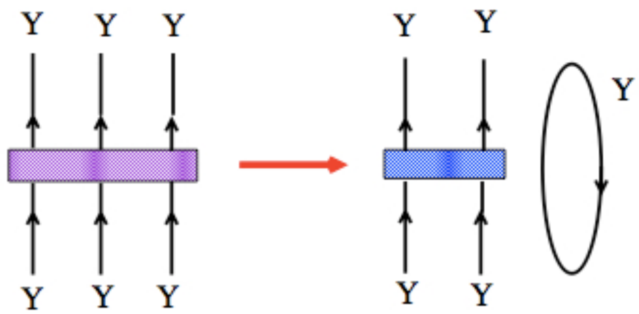
NNY ➔ NN, NY

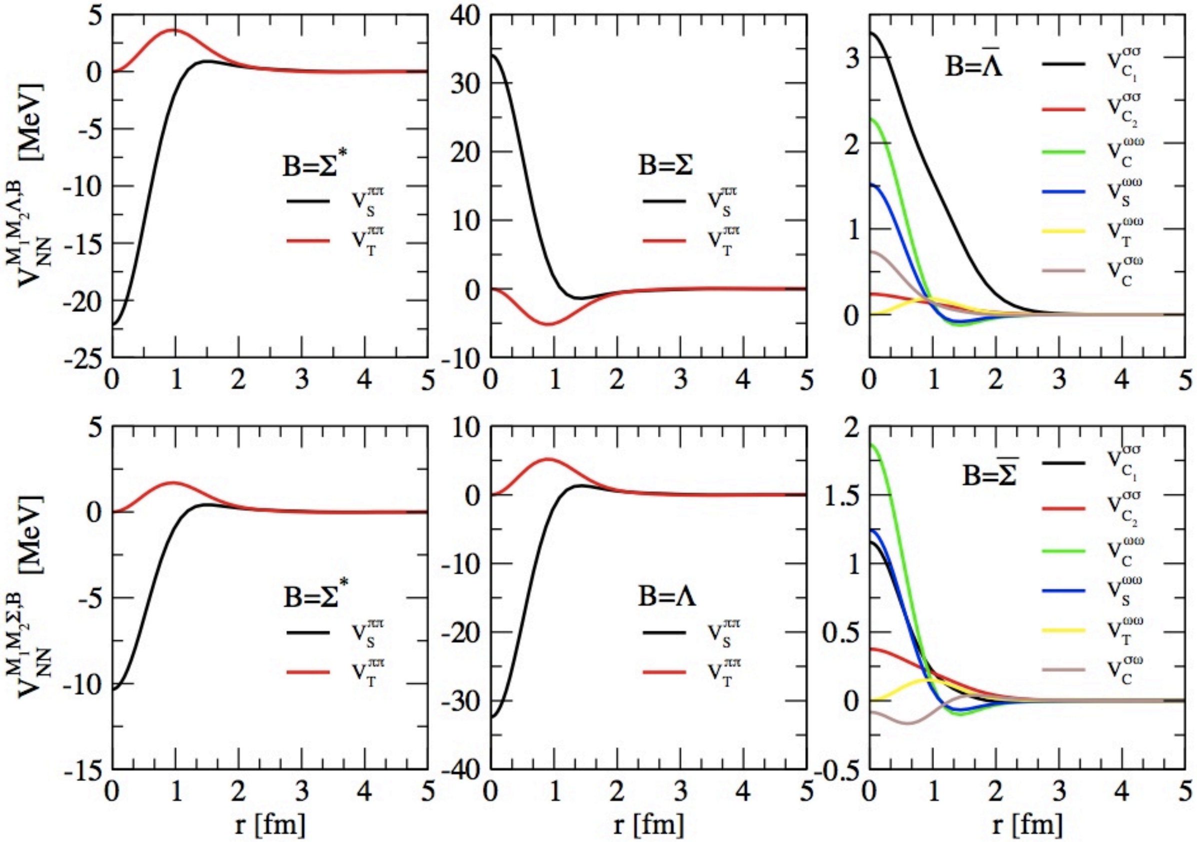


NYY ➔ NY, YY



YYY ➔ YY

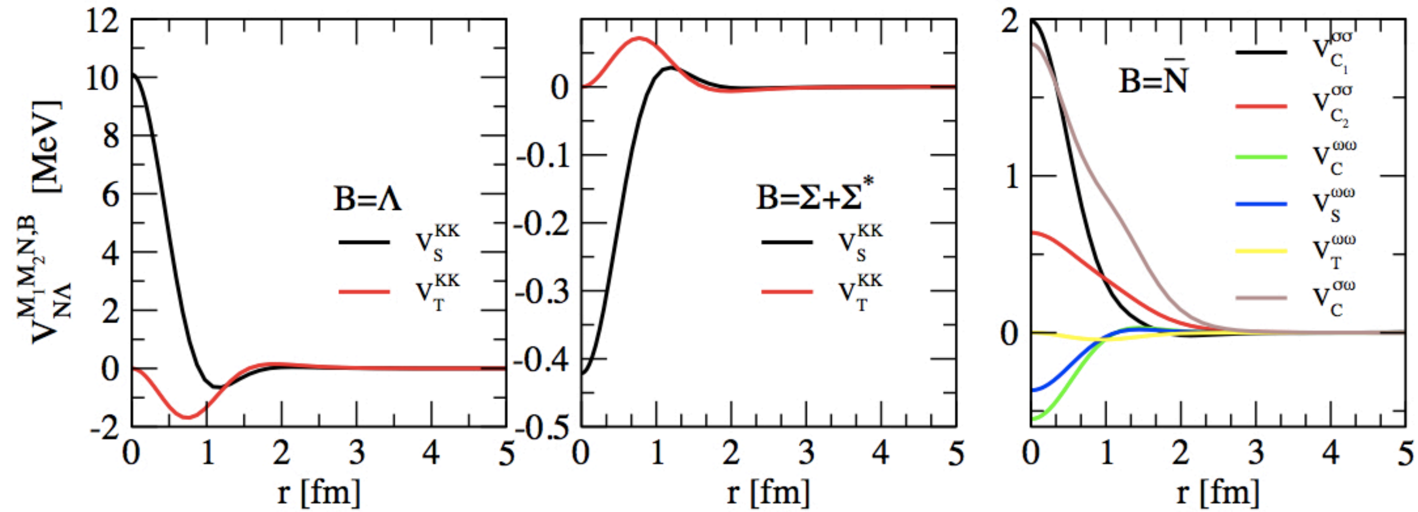




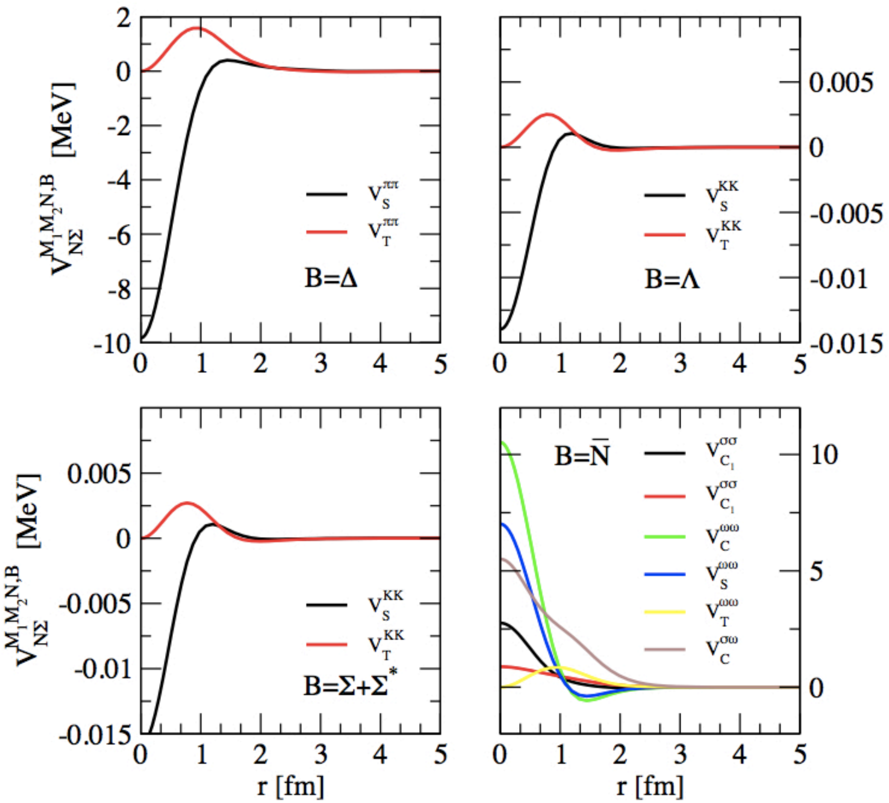
Effective NN density-dependent 2BF from NNY

- $V_{NN}^{\pi\pi Y,B}(\vec{r}) = C_{NNY}^{\pi\pi,B}\rho_Y\left[V_S^{\pi\pi}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{\pi\pi}(\vec{r})S_{12}(\hat{r})\right]\vec{\tau}_1\cdot\vec{\tau}_2$
- $V_{NN}^{\sigma\sigma Y,\bar{B}}(\vec{r}) = C_{NNY}^{\sigma\sigma,\bar{B}}\left[\rho_N V_{C_1}^{\sigma\sigma}(\vec{r}) + \rho_N^{5/3}V_{C_2}^{\sigma\sigma}(\vec{r})\right]$
- $V_{NN}^{\omega\omega Y,\bar{B}}(\vec{r}) = C_{NNY}^{\omega\omega,\bar{B}}\rho_Y\left[V_C^{\omega\omega}(\vec{r}) + V_S^{\omega\omega}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{\omega\omega}(\vec{r})S_{12}(\hat{r})\right]$
- $V_{NN}^{\sigma\omega Y,\bar{B}}(\vec{r}) = C_{NNY}^{\sigma\omega,\bar{B}}\rho_N V_C^{\sigma\omega}(\vec{r})$

Effective NΛ density-dependent 2BF from NNΛ



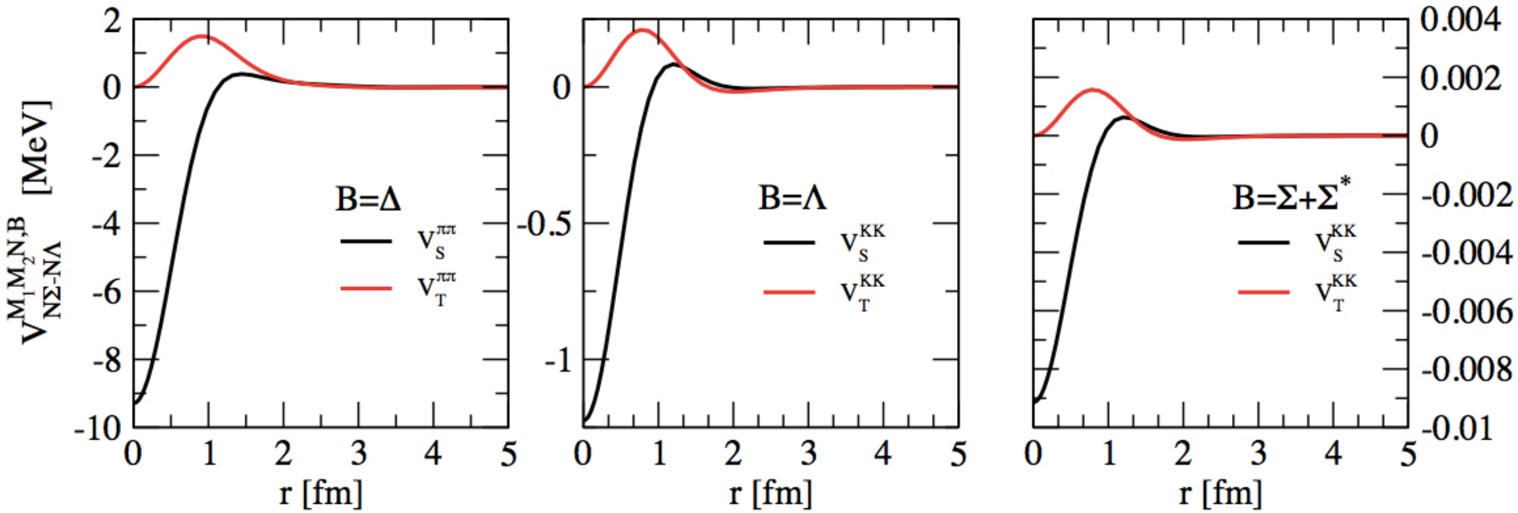
- $V_{N\Lambda}^{KKN,\Lambda}(\vec{r}) = C_{NN\Lambda}^{KK,\Lambda}\rho_N\left[V_S^{KK}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{KK}(\vec{r})S_{12}(\hat{r})\right]$
- $V_{N\Lambda}^{KKN,\Sigma/\Sigma^*}(\vec{r}) = C_{NN\Lambda}^{KK,\Sigma/\Sigma^*}\rho_N\left[V_S^{KK}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{KK}(\vec{r})S_{12}(\hat{r})\right]\vec{\tau}_1\cdot\vec{1}_2$
- $V_{N\Lambda}^{\sigma\sigma N,\bar{N}}(\vec{r}) = C_{NN\Lambda}^{\sigma\sigma,\bar{N}}\left[\rho_\Lambda V_{C_1}^{\sigma\sigma}(\vec{r}) + \rho_\Lambda^{5/3}V_{C_2}^{\sigma\sigma}(\vec{r})\right]$
- $V_{N\Lambda}^{\omega\omega N,\bar{N}}(\vec{r}) = C_{NN\Lambda}^{\omega\omega,\bar{N}}\rho_N\left[V_C^{\omega\omega}(\vec{r}) + V_S^{\omega\omega}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{\omega\omega}(\vec{r})S_{12}(\hat{r})\right]$
- $V_{N\Lambda}^{\sigma\omega N,\bar{N}}(\vec{r}) = C_{NN\Lambda}^{\sigma\omega,\bar{N}}\rho_\Lambda V_C^{\sigma\omega}(\vec{r})$



Effective NΣ density-dependent 2BF from NNΣ

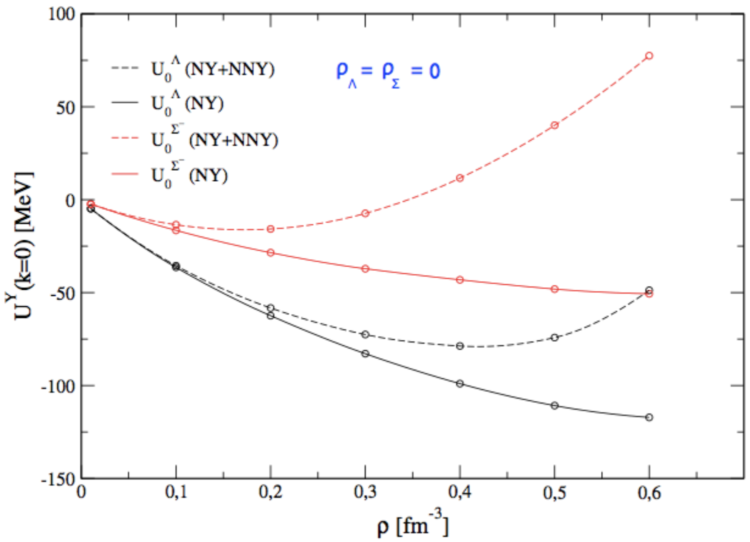
- $V_{N\Sigma}^{\pi\pi N,\Delta}(\vec{r}) = C_{NN\Sigma}^{\pi\pi,\Delta}\rho_N\left[V_S^{\pi\pi}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{\pi\pi}(\vec{r})S_{12}(\hat{r})\right]\vec{\tau}_1\cdot\vec{I}_2$
- $V_{N\Sigma}^{KKN,\Lambda/\Sigma}(\vec{r}) = C_{NN\Sigma}^{KK,\Lambda/\Sigma}\rho_N\left[V_S^{KK}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{KK}(\vec{r})S_{12}(\hat{r})\right]\vec{\tau}_1\cdot\vec{\tau}_2$
- $V_{N\Sigma}^{KKN,\Sigma^*}(\vec{r}) = C_{NN\Sigma}^{KK,\Sigma^*}\rho_N\left[V_S^{KK}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{KK}(\vec{r})S_{12}(\hat{r})\right]\vec{\tau}_1\cdot\vec{1}_2$
- $V_{N\Sigma}^{\sigma\sigma N,\bar{N}}(\vec{r}) = C_{NN\Sigma}^{\sigma\sigma,\bar{N}}\left[\rho_\Sigma V_{C_1}^{\sigma\sigma}(\vec{r}) + \rho_\Sigma^{5/3}V_{C_2}^{\sigma\sigma}(\vec{r})\right]$
- $V_{N\Sigma}^{\omega\omega N,\bar{N}}(\vec{r}) = C_{NN\Sigma}^{\omega\omega,\bar{N}}\rho_N\left[V_C^{\omega\omega}(\vec{r}) + V_S^{\omega\omega}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{\omega\omega}(\vec{r})S_{12}(\hat{r})\right]$
- $V_{N\Sigma}^{\sigma\omega N,\bar{N}}(\vec{r}) = C_{NN\Sigma}^{\sigma\omega,\bar{N}}\rho_\Sigma V_C^{\sigma\omega}(\vec{r})$

Effective density-dependent transition NΣ – NΛ from NNΣ – NNΛ

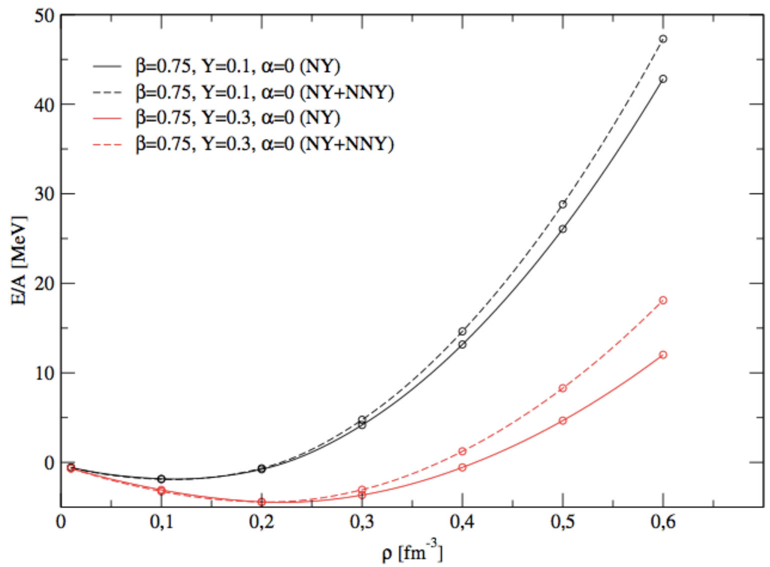


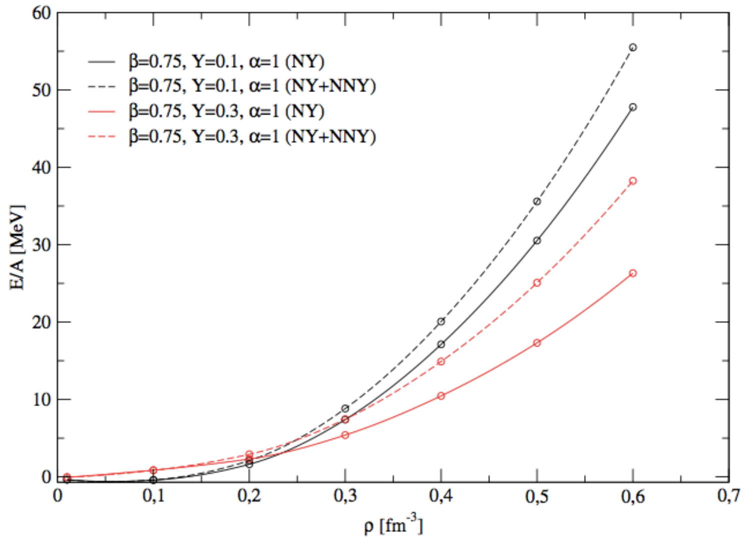
- $V_{N\Sigma\leftrightarrow N\Lambda}^{\pi\pi N,\Delta}(\vec{r}) = C_{NN\Sigma\leftrightarrow NN\Lambda}^{\pi\pi,\Delta}\rho_N\left[V_S^{\pi\pi}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{\pi\pi}(\vec{r})S_{12}(\hat{r})\right]\vec{\tau}_1\cdot\vec{I}_2$
- $V_{N\Sigma\leftrightarrow N\Lambda}^{KKN,\Lambda/\Sigma/\Sigma^*}(\vec{r}) = C_{NN\Sigma\leftrightarrow NN\Lambda}^{KK,\Lambda/\Sigma/\Sigma^*}\rho_N\left[V_S^{KK}(\vec{r})\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{KK}(\vec{r})S_{12}(\hat{r})\right]\vec{\tau}_1\cdot\vec{1}_2$

Effect of TBF on Mean Field & E/A



- ✓ Only NNY considered (preliminar)
- ✓ Repulsion at high densities due to Z-diagram contribution as in NNN





Work is in progress, many more contributions have to be considered, but we can still try to estimate the effect of hyperonic TBF in NS

1-. Construct the hyperonic matter EoS within the BHF at 2 body level (Av18 NN + NSC89 YN)

2-. Add simple phenomenological density-dependent contact terms that mimic the effect of TBF.

Density-dependent contact terms: (Balberg & Gal 1997)

Potential of a baryon B_y in a sea of baryons B_x of density ρ_x

$$V_y(\rho_x) = a_{xy}\rho_x + b_{xy}\rho_x^{\gamma_{xy}}$$

attraction

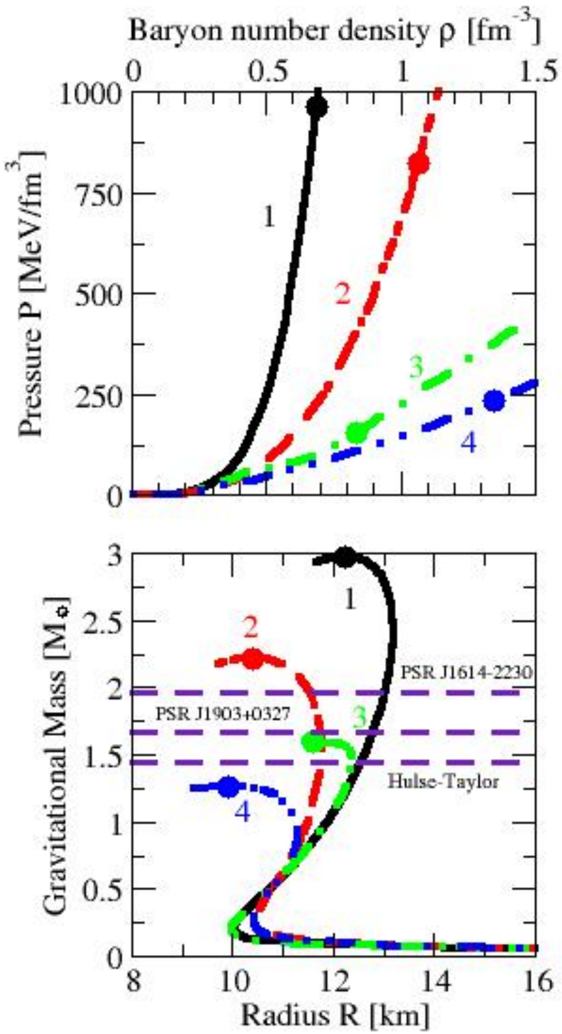
repulsion

larger than 1

Folding $V_y(\rho_x)$ with ρ_x, $V_x(\rho_y)$ with ρ_y and combining with weight factors ρ_x/ρ and ρ_y/ρ

$$\varepsilon_{xy}(\rho_x,\rho_y) = a_{xy}\rho_x\rho_y + b_{xy}\rho_x\rho_y\left(\frac{\rho_x^{\gamma_{xy}} + \rho_y^{\gamma_{xy}}}{\rho_x + \rho_y}\right)$$

Effect of hyperonic TBF on M_{max}



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
	1	1.77	1.41
2.5	0	-	1.29 (2.46)
	1/3	1.84	1.38
	2/3	2.08	1.44
	1	2.19	1.48
3	0	-	1.34 (2.72)
	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

Hyperonic TBFs seem not to be the full solution of the "Hyperon Puzzle", although they probably contribute to its solution

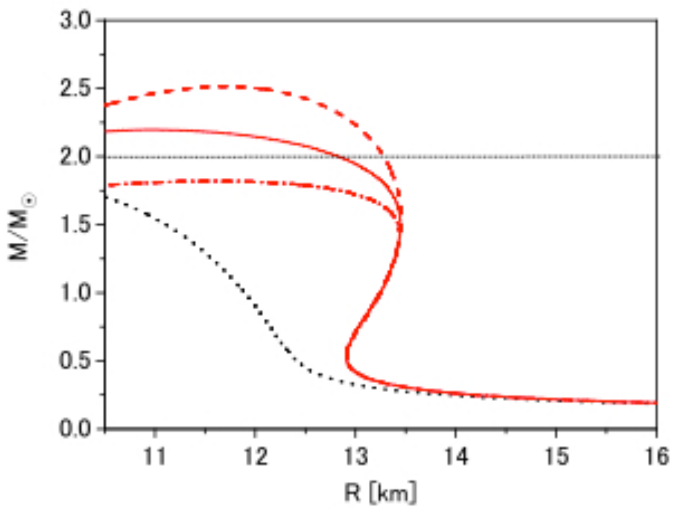
$$1.27 < M_{max} < 1.6 M_\odot$$

IV, Logoteta, et al., (2011)

A comment must be done at this point

Yamamoto et al. (2015)

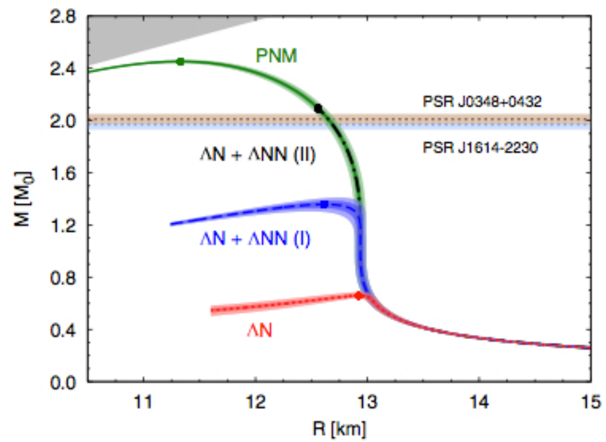
BHF with NN+YN+universal repulsive TBF (multipomeron exchange mecanism)



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

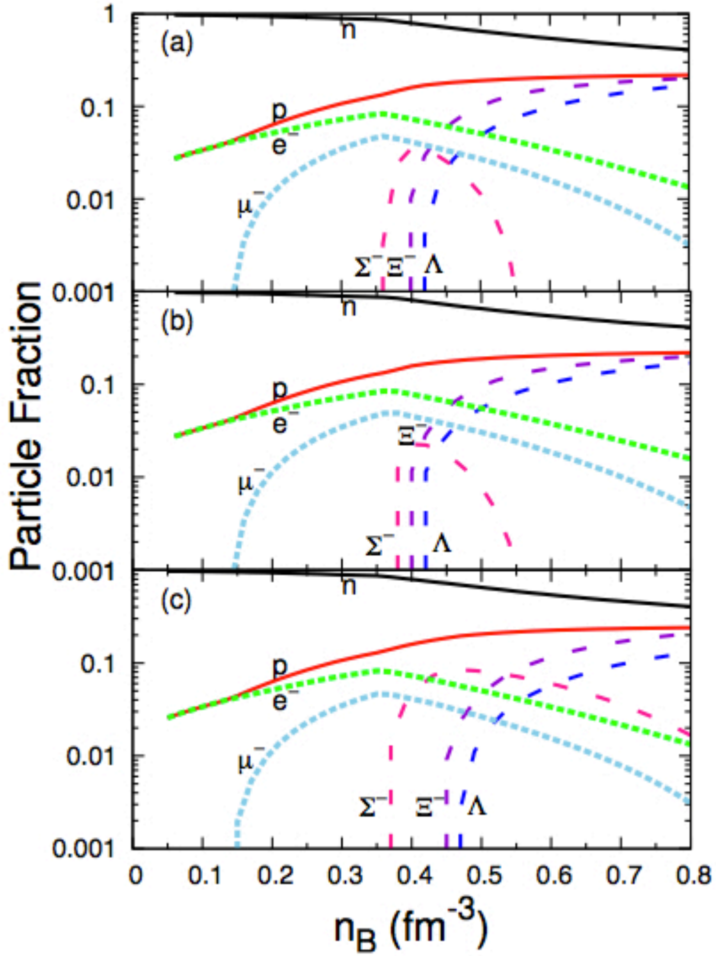
Lonardoni et al. (2015)

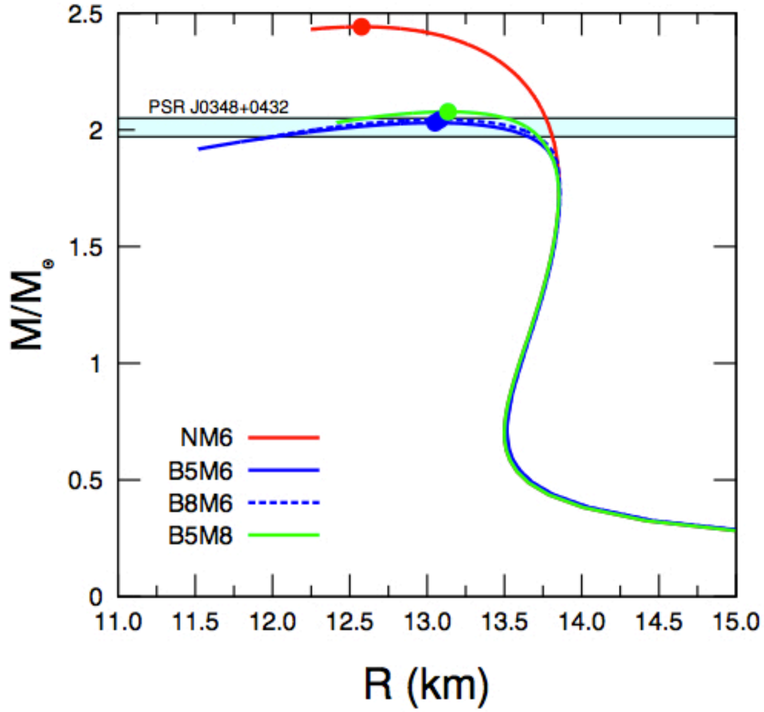
First Quantum Monte Carlo calculation on neutron+Λ matter



Some of the parametrizations of the Λnn force give maximum masses compatible with $2M_\odot$ but the onset of Λ is above the largest density considered in the calculation (~ 0.56 fm^{-3}). So in fact no Λs are present in NS interior

It should be mentioned also the recent DBHF calculation of hyperonic matter by Katayama & Saito (2014)

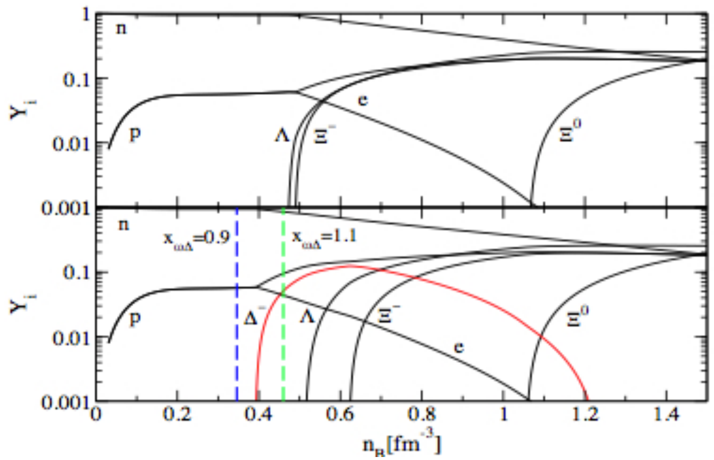


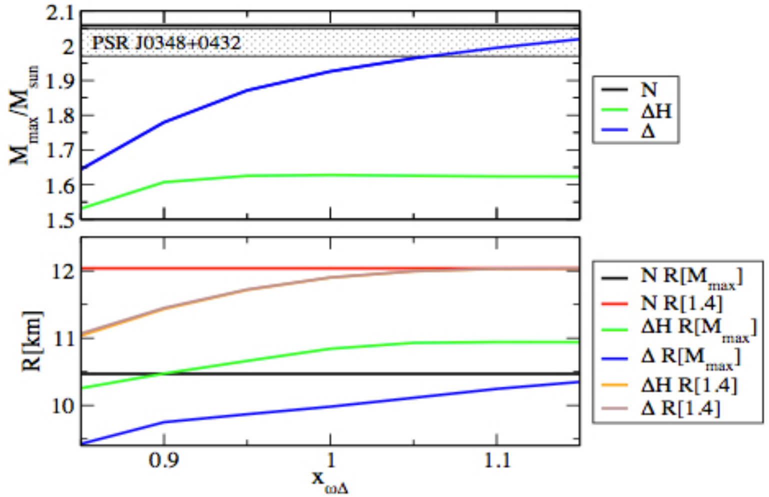


- DBHF includes some TBF effects in a natural way
- M_{max} compatible with $2M_\odot$
- But the construction of YN is a bit obscure in this work

Is there also a Δ isobar puzzle ?

The recent work by Drago et al. (2014) calculation have studied the role of the Δ isobar in neutron star matter





- ❖ Constraints from L indicate an early appearance of Δ isobars in neutron stars matter at ~ 2-3 ρ_0 (same range as hyperons)
- ❖ Appearance of Δ isobars modify the composition & structure of hadronic stars
- ❖ M_{max} is dramatically afected by the presence of Δ isobars

If Δ potential is close to that indicated by π−, e-nucleus or photoabsortion nuclear reactions then EoS is too soft ⟶ Δ puzzle similar to the hyperon one

Summary & Conclusions

- Construction of two-meson exchange hyperonic TBF

  Repulsion is obtained at high densities (Z-diagram)

  D. Logoteta, Ph.D. Thesis (Univ. Coimbra, Sept. 2013)

- Simple model to establish numerical lower and upper limits to the effect of hyperonicTBF on the maximum mass of NS.

  Assuming the strength of hyperonic TBF ≤ nucleonic TBF:

  $\boxed{1.27\ M_\odot < M_{max} < 1.60\ M_\odot}$ compatible with 1.4-1.5 $M_\odot$

  but incompatible with observation of very massive NS

  PSR J1903+0327 (1.67±0.01) $M_\odot$
  PSR J1614-2230 (1.97±0.04) $M_\odot$
  PSR J0348+0432 (2.01±0.04) $M_\odot$

- There is not yet a general agreement between different approaches/models

Take away message

Hyperonic Three-Body Forces seem not to be the full solution to the "Hyperon Puzzle", although they probably can contribute to it

- You for your time & attention
- The organizers for their invitation & support

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