Exotic Baryons in Magnetars

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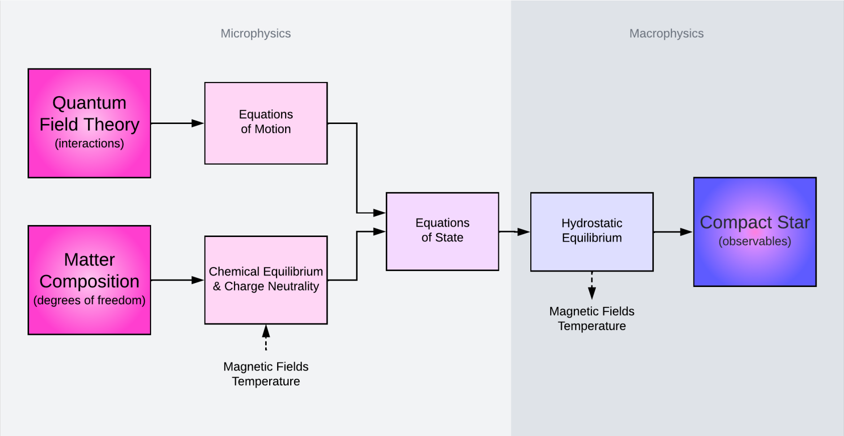
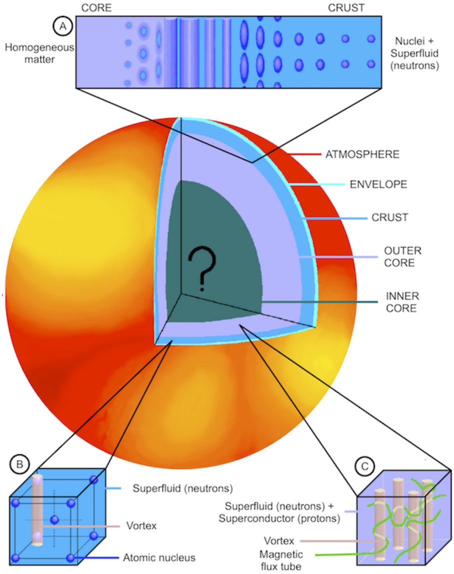
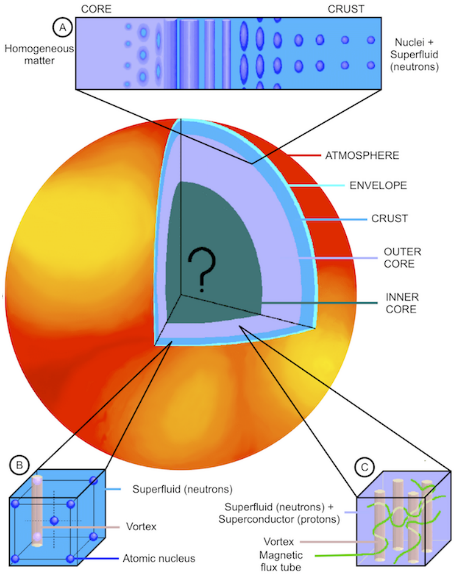
in collaboration with the groups of
Débora Menezes (Santa Catarina Federal U.), Constança Providência (Coimbra U.),
Veronica Dexheimer (Kent State U.) and Debarati Chatterjee (IUCAA India)

1. Exotic baryons in Neutron Stars
   - Relativistic effective models in compact star description
   - The meson-baryon coupling scheme
   - Some results

2. Exotic Baryons in Magnetars
   - Matter composition under extreme magnetic fields
   - Macroscopic structure effects of magnetic fields
   - Magnetic field effects on the deconfinement transition


Microphysics
Macrophysics
Quantum
Field Theory
(interactions)
Equations
of Motion
Matter
Composition
(degrees of freedom)
Chemical Equilibrium
& Charge Neutrality
Magnetic Fields
Temperature
Equations
of State
Hydrostatic
Equilibrium
Magnetic Fields
Temperature
Compact Star
(observables)


CORE
CRUST
A
Homogeneous matter
Nuclei + Superfluid (neutrons)
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
B
Superfluid (neutrons)
Vortex
Atomic nucleus
C
Superfluid (neutrons) + Superconductor (protons)
Vortex
Magnetic flux tube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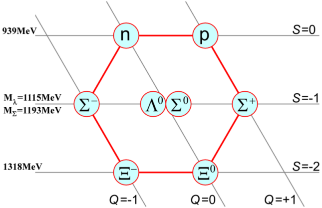
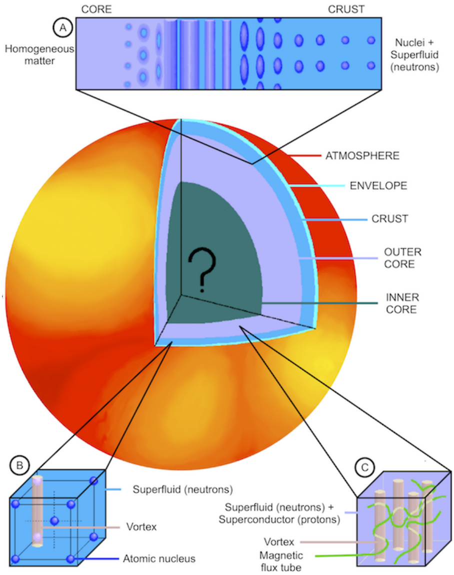

939MeV
M_λ=1115MeV
M_Σ=1193MeV
1318MeV
n
p
Σ^-
Λ^0
Σ^0
Σ^+
Ξ^-
Ξ^0
S=0
S=-1
S=-2
Q=-1
Q=0
Q=+1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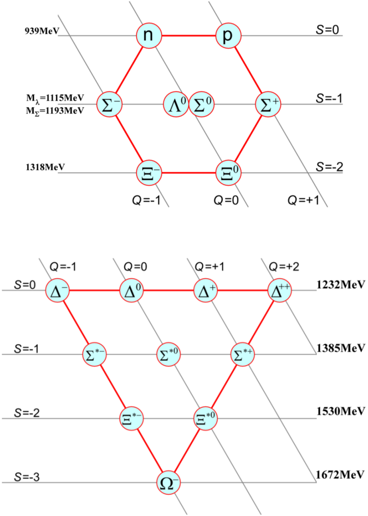
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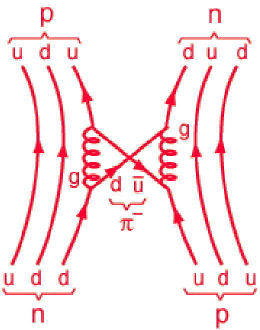
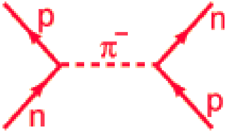
S=0
Δ^-
Δ^0
Δ^+
Δ^{++}
1232MeV
S=-1
Σ^{*-}
Σ^{*0}
Σ^{*+}
1385MeV
S=-2
Ξ^{*-}
Ξ^{*0}
1530MeV
S=-3
Ω^-
1672MeV


p
u d u
n
d u d
g
g
d ū
π⁻
u d d
n
u d u
p


p
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π⁻
n
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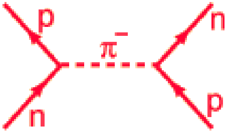


Model	n_0	B/A	K	$\mathcal{S}$	L	M/m
GM1	0.153	16.33	300.5	32.5	94	0.70
L3$\omega\rho$	0.156	16.20	256	31.2	74	0.69
DDME2	0.152	16.14	251	32.3	51	0.57
Constr.	0.148−0.170	15.8−16.5	220−260	28.6−34.4	36.0−86.8	0.6−0.8

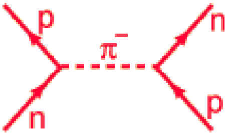
- symmetric nuclear matter properties at saturation density for the models employed in this work.

$$\mathcal{L}_{\text{Yukawa}} = -(g_{BM})(\bar{\psi}_B\psi_B)M, \quad (1)$$

where

- M is the field of an arbitrary (vector) meson: $\omega, \vec{\rho}, \phi$
- ψ_B is the field of the baryon B: p, n, *hyperons*, $\Delta, \cdots$
- g_{BM} is the Yukawa coupling constant of the baryon B with the meson M, given by

$$g_{BM} = \chi_{BM} g_{NB}.$$



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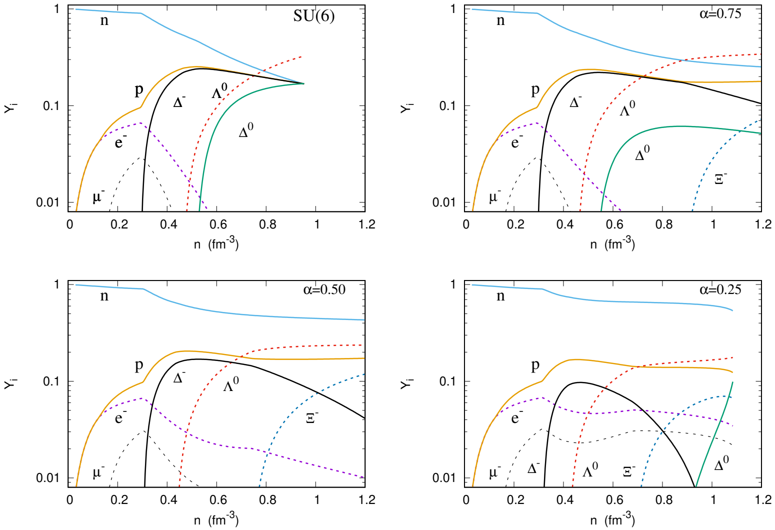
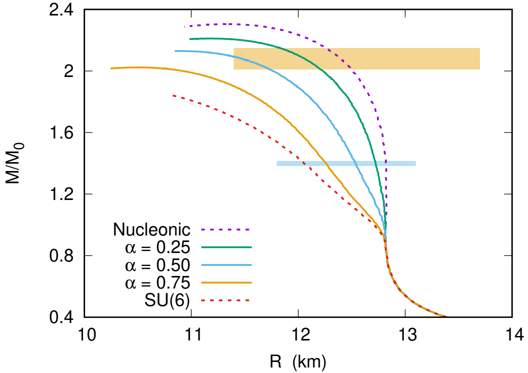


Particle population for different values of α for Δ-admixed hyperonic stellar matter.

Lopes, KDM, Menezes, Phys. Rev. D 107, 036011 (2023)

α_v	SU(6)	0.75	0.50	0.25	Nucl.
	α				
$M_{max}/M_\odot$	1.84*	2.02	2.13	2.21	2.30
n_c (fm^{-3})	0.95*	1.14	1.05	0.98	0.94
R (km)	10.81*	10.50	10.90	11.18	11.34
$R_{1.4}$ (km)	12.05	12.25	12.53	12.73	12.82
$\Lambda_{1.4}$	311	360	428	489	516



$$\int d^3k \rightarrow \frac{|q|B}{(2\pi)^2} \sum_{\nu} \int dk_z, \qquad \text{where} \qquad \nu = n + \frac{1}{2} - \frac{s}{2} \frac{q_b}{|q_b|} \tag{2}$$

$$\nu_{\max b}(s) = \left\lfloor \frac{\left(E^*_{F\,b} + s\kappa_b B\right)^2 - M_b^{*\,2}}{2|q_b|B} \right\rfloor \tag{3}$$

$q_b = 0$:

$$k^2_{F,b}(s) = {E^*_{F\,b}}^2 - \left(M^*_b - s\kappa_b B\right)^2 \tag{4}$$

$$n_b = \frac{1}{2\pi^2} \sum_s \left\{ \frac{k^3_{F\,b}(s)}{3} - \frac{s\kappa_b B}{2} \left[\left(M^*_b - s\kappa_b B\right) k_{F\,b}(s) {E^*_{F\,b}}^2 \left(\arcsin\left(\frac{M^*_b - s\kappa_b B}{E^*_{F\,b}} \right) - \frac{\pi}{2} \right) \right] \right\} \tag{5}$$

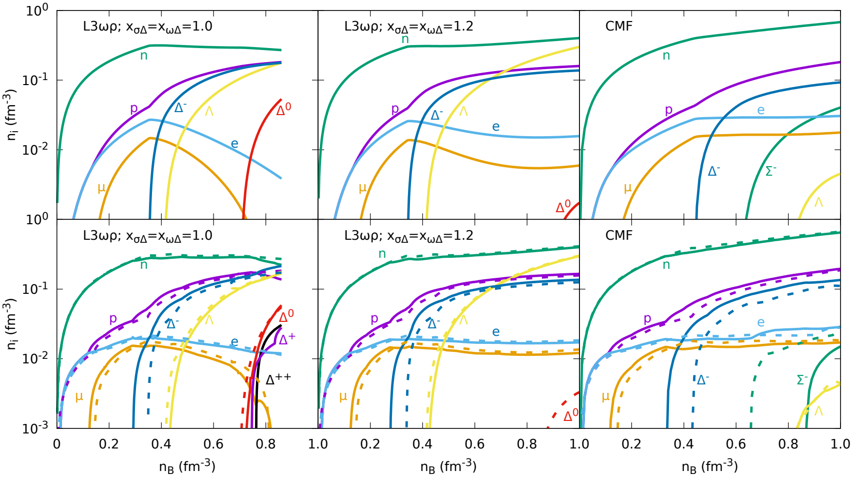
$$n_{s\,b} = \frac{M^*_b}{4\pi^2} \sum_s \left[E^*_{F\,b} k_{F\,b}(s) - \left(M^*_b - s\kappa_b B\right)^2 \ln \left| \frac{k_{F\,b}(s) + E^*_{F\,b}}{M^*_b - s\kappa_b B} \right| \right] \tag{6}$$

$q_b \neq 0$:

$$k^2_{F,b}(\nu, s) = {E^*_{F\,b}}^2 - \left(\sqrt{M_b^{*\,2} + 2\nu|q_b|B} - s\kappa_b B \right)^2 \tag{7}$$

$$n_b = \frac{|q_b|B}{2\pi^2} \sum_{\nu, s} k_{F\,b}(\nu, s) \tag{8}$$

$$n_{s\,b} = \frac{|q_b|BM^*_b}{2\pi^2} \sum_{s,\nu} \frac{\sqrt{M_b^{*\,2} + 2\nu|q_b|B} - s\kappa_b B}{\sqrt{M_b^{*\,2} + 2\nu|q_b|B}} \ln \left| \frac{k_{F\,b}(\nu, s) + E^*_{F\,b}}{\sqrt{M_b^{*\,2} + 2\nu|q_b|B} - s\kappa_b B} \right| \tag{9}$$



- Particle composition of neutron-star matter with Δs, with $B = 0$ (top panels) and magnetic field $B = 3 \times 10^{18}$ G (bottom panels), when considering (solid lines) or disregarding (dashed lines) the effects of the AMMs.

Q: How to deal with the magnetic field effects in the mechanical equilibrium conditions for the compact stars?

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

is derived imposing isotropic matter and spherical symmetry, both things broken by *B*!

ignore the anisotropy? assume chaotic B distributions?

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B is 10^{15} G in the star surface, but reaches(?) 10^{18} G in the core. What's the profile that interpolate this values?

$$B_z(\varepsilon) = B^{surf} + B_0\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\alpha}$$

does not preserve $\nabla \cdot \vec{B} = 0$!

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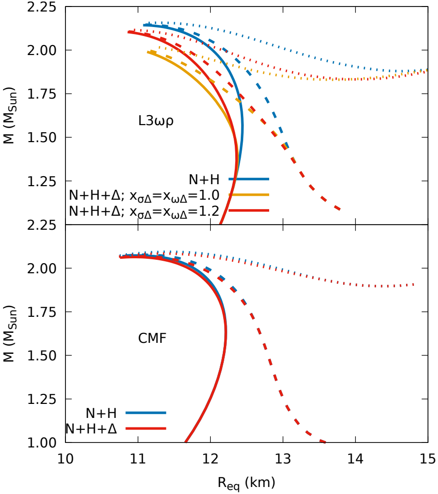
A: Solve the Einstein equations together with the Maxwell equations $\rightarrow$ LORENE

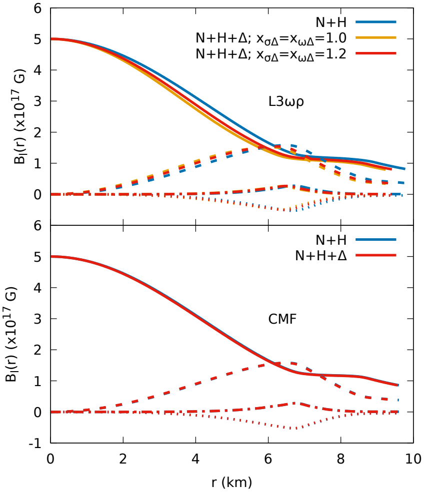


- Stellar mass as a function of equatorial radius for different compositions and interaction strengths, for central magnetic fields $B = 0$ (solid lines), $B = 5 \times 10^{17}$ G (dashed lines), and $B = 10^{18}$ G (dotted lines).

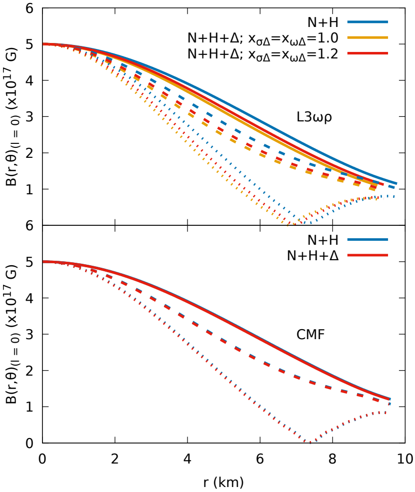
	n_c (fm^{-3})		ε_c (MeV/fm^3)	
B (G)	N+H	N+H+Δ	N+H	N+H+Δ
0	0.672	0.618 (0.614)	742	658 (657)
5×10^{17}	0.701	0.659 (0.653)	783	712 (708)
1×10^{18}	0.747	0.714 (0.707)	850	786 (783)
0	0.629	0.625	678	672
5×10^{17}	0.680	0.677	747	741
1×10^{18}	0.749	0.746	843	837

- Central baryon (n_c) and energy (ε_c) densities as a function of magnetic field strength for neutron stars of radius 12 km with L3$\omega\rho$ model for $x_{\sigma\Delta} = x_{\omega\Delta} = 1.0(1.2)$ in the top panel and CMF model in the bottom panel.

$$B(r,\theta) \simeq \sum B_l(r) Y_l^0(\theta) \tag{10}$$

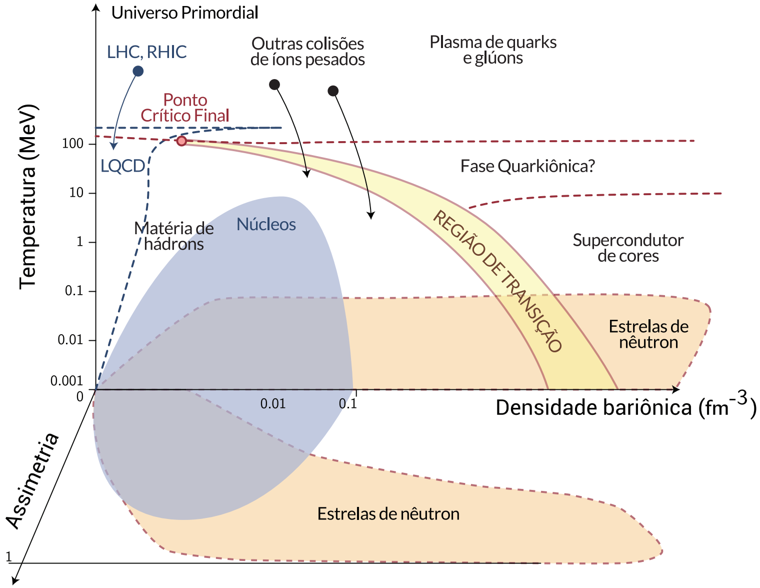


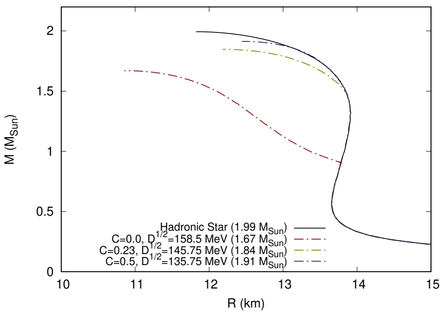
Solid, dashed, dashed-dotted and dotted are $l = 0, 2, 4, 6$.



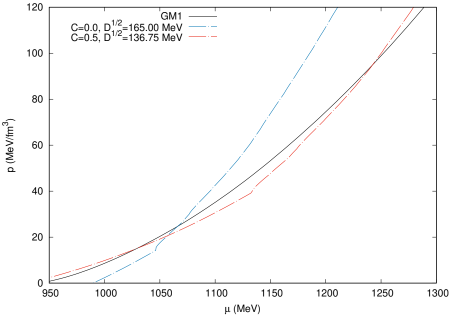
Solid, dashed and dotted are the $l = 0$ term at the $\theta = 0, \pi/4, \pi/2$ orientations.

- Magnetic field distribution inside a neutron star of mass $1.8M_\odot$ and central magnetic field of $B = 5 \times 10^{17}$ G.


Universo Primordial
LHC, RHIC
Outras colisões
de íons pesados
Plasma de quarks
e glúons
Ponto
Crítico Final
100
LQCD
10
1
0.1
0.01
0.001
0
Temperatura (MeV)
Fase Quarkiônica?
Matéria de
hádrons
Núcleos
REGIÃO DE TRANSIÇÃO
Supercondutor
de cores
Estrelas de
nêutron
0.01
0.1
Densidade bariônica (fm^{-3})
Assimetria
Estrelas de nêutron
1



- Mass-radius diagram for hybrid EoS with chemical equilibrium in both phases, showing results without magnetic field effects.



- Example of equations of state of parameter choices that allow the hadron-quark phase transition to occur at $B = 3 \times 10^{18}$ G.

$$m_i = m_{i0} + \frac{D}{n_b^{1/3}} + C n_b^{1/3} = m_{i0} + m_I, \tag{11}$$

	B = 0	B = 3 $\times$ 10^{18} G	B-W
$C = 0$ $\sqrt{D} = 155$ MeV	no crossing	no crossing	yes
$C = 0$ $\sqrt{D} = 158.5$ MeV	$\mu_0 = 960$ $p_0 = 1.55$	$\mu_0 = 958$ $p_0 = 1.80$	yes
$C = 0$ $\sqrt{D} = 165$ MeV	$\mu_0 = 1062$ $p_0 = 21.98$	$\mu_0 = 1066$ $p_0 = 24.70$	no
$C = 0.23$ $\sqrt{D} = 155$ MeV	$\mu_0 = 1130$ $p_0 = 43.62$	$\mu_0 = 1145$ $p_0 = 51.32$	no
$C = 0.365$ $\sqrt{D} = 142$ MeV	$\mu_0 = 1105$ $p_0 = 34.98$	$\mu_0 = 1109$ $p_0 = 38.30$	yes
$C = 0.5$ $\sqrt{D} = 135.75$ MeV	$\mu_0 = 1202$ $p_0 = 72.66$	$\mu_0 = 1242$ $p_0 = 94.93$	yes
$C = 0.68$ $\sqrt{D} = 130$ MeV	$\mu_0 = 1440$ $p_0 = 215.50$	$\mu_0 = 1475$ $p_0 = 247.53$	yes

- Values for μ_0 (in MeV) and p_0 (in MeV/fm^3) for which the conditions of phase coexistence are satisfied at $T = 0$. The latter column specifies whether or not the Bodmer-Witten conjecture is satisfied.

- DEXHEIMER, V.; MARQUEZ, K. D.; MENEZES, D. P. **Delta baryons in neutron-star matter under strong magnetic fields**. EUROPEAN PHYSICAL JOURNAL A 57 216, 2021. [arXiv:2103.09855]
- BACKES, B. C. T.; MARQUEZ, K. D.; MENEZES, D. P. **Effects of strong magnetic fields on the hadron-quark deconfinement transition**. EUROPEAN PHYSICAL JOURNAL A 57 229, 2021. [arXiv:2103.14733]
- MARQUEZ, K. D.; PELICER, M. R.; GHOSH, S.; PETERSON, J.; CHATTERJEE, D.; DEXHEIMER, V.; MENEZES, D. P. **Exploring the effects of Delta Baryons in magnetars**. PHYSICAL REVIEW C 106 035801, 2022. [arXiv:2205.09827]

- The understanding of the meson-delta coupling parameters can be refined by symmetry group considerations, as it is made for the hyperon coupling schemes.
- The magnetic field effects on Δ-admixed matter can be more robustly understood by having the complete solution of the Einstein equations together with the Maxwell equations.
- **WIPs**: finite temperature effects, inclusion of baryons beyond the Δs, dynamical implications ...

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Muito Obrigado!

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CFisUC PPGFSC CNPq INCT-FNA

$$\mu_b = \mu_n - q_b \mu_e \tag{12}$$

$$\sum_{i=b,l} q_i n_i = 0 \tag{13}$$

$$\varepsilon = \sum_b \frac{1}{\pi^2} \int_0^{p_{F_b}} dp\, p^2 \sqrt{p^2 + M_b^2} + \frac{1}{2} m_\sigma^2 \sigma_0^2 + \frac{\lambda_1}{3} \sigma_0^3 + \frac{\lambda_2}{4} \sigma_0^4$$
$$- \frac{1}{2} m_\omega^2 \omega_0^2 - \frac{1}{2} m_\phi^2 \phi_0^2 - \frac{1}{2} m_\rho^2 \rho_0^2 - g_{\omega\rho} \omega_0^2 \rho_0^2 + \varepsilon_{\mathrm{leptons}}, \tag{14}$$

$$P = -\varepsilon + \sum_b \mu_b n_b \tag{15}$$

$$\frac{dP}{dr} = -\frac{[\varepsilon(r) + P(r)]\left[m(r) + 4\pi r^3 P(r)\right]}{r\,[r - 2m(r)]}, \tag{16}$$

$$m(r) = \int_0^r dr' 4\pi r'^2 \varepsilon(r')\,. \tag{17}$$

	M_b (MeV)	$q_b(e)$	$I_{3\,b}$	S_b	μ_b/μ_N	κ_b/μ_N
p	939	$+1$	$+1/2$	1/2	2.79	1.79
n	939	0	$-1/2$	1/2	-1.91	-1.91
Λ	1116	0	0	1/2	-0.61	-0.61
Σ^+	1193	$+1$	$+1$	1/2	2.46	1.67
Σ^0	1193	0	0	1/2	1.61	1.61
Σ^-	1193	-1	-1	1/2	-1.16	-0.37
Ξ^0	1315	0	$+1/2$	1/2	-1.25	-1.25
Ξ^-	1315	-1	$-1/2$	1/2	-0.65	0.06
Δ^{++}	1232	$+2$	$+3/2$	3/2	4.99	3.47
Δ^+	1232	$+1$	$+1/2$	3/2	2.49	1.73
Δ^0	1232	0	$-1/2$	3/2	0.06	0.06
Δ^-	1232	-1	$-3/2$	3/2	-2.45	-1.69

$$\kappa_b = \mu_b - q_b \mu_N \frac{M_N}{M_b} \tag{18}$$

Phys. Rev. D 107, 036011 (2023) [arXiv:2211.17153]

	α			
	1.00	0.75	0.50	0.25
$g_{\Lambda\omega}/g_{N\omega}$	0.667	0.687	0.714	0.75
$g_{\Sigma\omega}/g_{N\omega}$	0.667	0.812	1.0	1.25
$g_{\Xi\omega}/g_{N\omega}$	0.333	0.437	0.571	0.75
$g_{\Delta\omega}/g_{N\omega}$	1.0	1.125	1.285	1.5
$g_{\Delta^*\omega}/g_{N\omega}$	1.0	1.125	1.285	1.5
$g_{\Sigma^*\omega}/g_{N\omega}$	0.667	0.75	0.857	1.0
$g_{\Xi^*\omega}/g_{N\omega}$	0.333	0.375	0.428	0.667
$g_{\Omega\omega}/g_{N\omega}$	0.0	0.0	0.0	0.0
$g_{\Lambda\phi}/g_{N\omega}$	-0.471	-0.619	-0.808	-1.06
$g_{\Sigma\phi}/g_{N\omega}$	-0.471	-0.441	-0.404	-0.354
$g_{\Xi\phi}/g_{N\omega}$	-0.943	-0.972	-1.01	-1.06
$g_{\Sigma^*\phi}/g_{N\omega}$	-0.471	-0.530	-0.606	-0.707
$g_{\Xi^*\phi}/g_{N\omega}$	-0.943	-1.060	-1.212	-1.414
$g_{\Omega\phi}/g_{N\omega}$	-1.414	-1.590	-1.818	-2.212
$g_{\Lambda\rho}/g_{N\rho}$	0.0	0.0	0.0	0.0
$g_{\Sigma\rho}/g_{N\rho}$	2.0	1.5	1.0	0.5
$g_{\Xi\rho}/g_{N\rho}$	1.0	0.5	0.0	-0.5
$g_{\Delta\rho}/g_{N\rho}$	1.0	1.0	1.0	1.0
$g_{\Delta^*\rho}/g_{N\rho}$	3.0	3.0	3.0	3.0
$g_{\Sigma^*\rho}/g_{N\rho}$	2.0	2.0	2.0	2.0
$g_{\Xi^*\rho}/g_{N\rho}$	1.0	1.0	1.0	1.0
$g_{\Omega\rho}/g_{N\rho}$	0.0	0.0	0.0	0.0

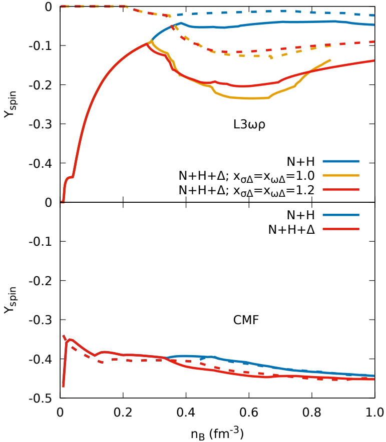
$$U_B(n_0) = g_{B\omega}\omega_0 - g_{B\sigma}\sigma_0$$

$$U_\Lambda = -28 \text{ MeV},$$
$$U_\Sigma = +30 \text{ MeV},$$
$$U_\Xi = -4 \text{ MeV},$$
$$U_\Delta = -98 \text{ MeV}$$

	α			
	1.00	0.75	0.50	0.25
$g_{\Lambda\sigma}/g_{N\sigma}$	0.610	0.625	0.646	0.674
$g_{\Sigma\sigma}/g_{N\sigma}$	0.406	0.518	0.663	0.855
$g_{\Xi\sigma}/g_{N\sigma}$	0.269	0.350	0.453	0.590
$g_{\Delta\sigma}/g_{N\sigma}$	1.110	1.208	1.331	1.5
$g_{\Delta^*\sigma}/g_{N\sigma}$	1.110	1.208	1.331	1.5
$g_{\Sigma^*\sigma}/g_{N\sigma}$	?	?	?	?
$g_{\Xi^*\sigma}/g_{N\sigma}$	?	?	?	?
$g_{\Omega\sigma}/g_{N\sigma}$	?	?	?	?

L3$\omega\rho$

$$Y_{\rm spin} = \frac{\sum_{b,s} s n_b(s)}{\sum_{b,s} n_b(s)} \,, \tag{19}$$



- Spin polarization fraction as a function of baryon number density for neutron-star matter with magnetic field $B = 3 \times 10^{18}$ G, when considering (solid lines) or disregarding (dashed lines) the effects of the AMMs.