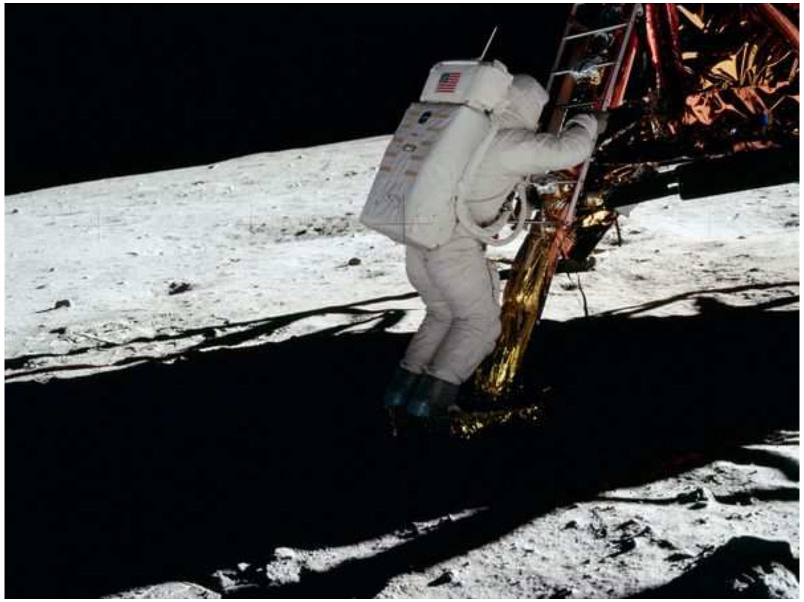
Quark matter subject to strong magnetic fields

Parkes Telescope - Austrália

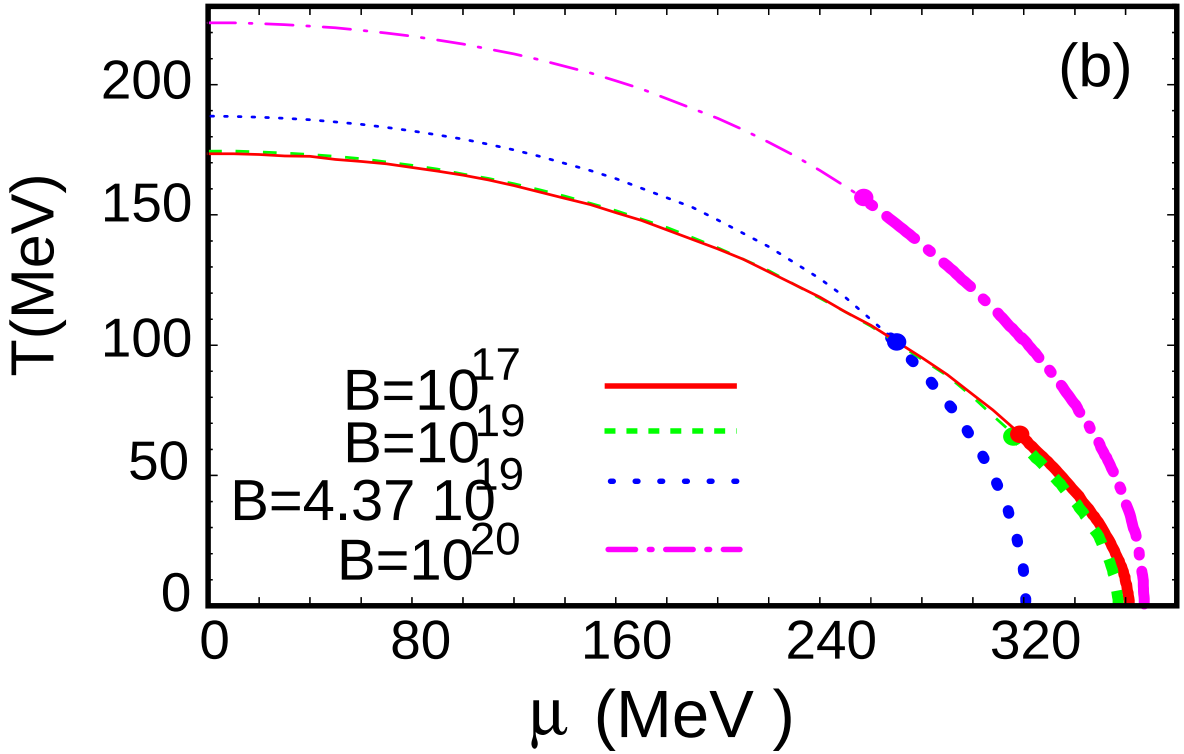


first moon walk

Débora Peres Menezes - Universidade Federal de Santa Catarina

EMMI Rapid Reaction Task Force Meeting on Quark Matter in Neutron Stars - FIAS - October 2013

QCD Phase Diagram - NJL model



T_c decreases at high μ; size of 1^{st} order line increases with B; T_{pc} (cross-over) increases at $\mu = 0$

S.S. Avancini, D.P. Menezes, M.B. Pinto and C. Providência; Phys. Rev. D 85, 091901(R) (2012).

- Within effective quark models ($T = 0, \mu = 0$), B stabilizes the chirally asymmetric vaccum by antialigning the helicities of a $q\bar{q}$ pair (in contrast to what happens in ordinary superconductors, where B favors the alignment of spins, opposing pair formation).

- *Magnetic catalysis* - effective models - $B \uparrow, T \uparrow$

- *Antimagnetic catalysis* - Lattice QCD - $B \uparrow, T \downarrow$ - this behaviour can be reproduced within the EPNJL model (but not explained) - **M. Ferreira, P. Costa, D.P. Menezes, C. Providencia and N. Scoccola, arXiv:1305.4751[hep-ph]**

- The *(anti)magnetic catalysis* is a reflex of the behaviour of quark condensates with temperature in an external B and naturally leads to the question of how B would influence chiral/deconfinement phase transitions at finite temperatures and/or chemical potentials.

- ...what leads us to try to understand (proto)NS.

Main NS manifestations:

- **Pulsars** - powered by rotation energy (1900 observed in radio-frequency)

- **Accreting X-Ray Binaries** - powered by gravitational energy (typical rotation periods 0.0015 - 1000 s)

Magnetars don't fit into these categories! They are normally isolated NS (no evidence for binarity so far) whose main power source is the magnetic field.

There are 2 classes of magnetars (25 confirmed):

- **Soft gamma-ray repeaters** (discovered in 1979 as transient X-ray sources and *giant flares*);

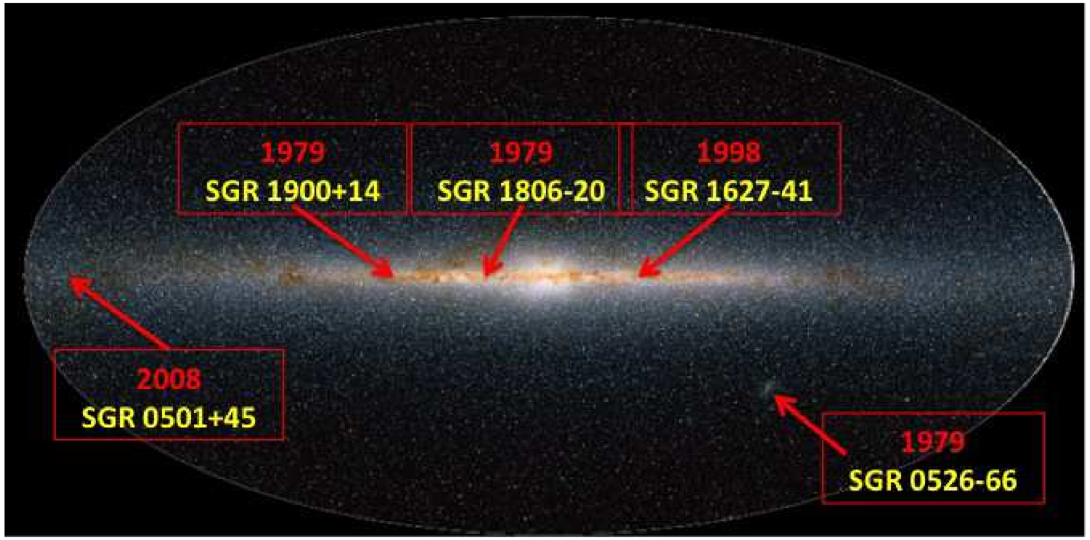
- **Anomalous X-ray pulsars** (identified in 1990 as a class of persistent X-ray with no sign of a binary companion);

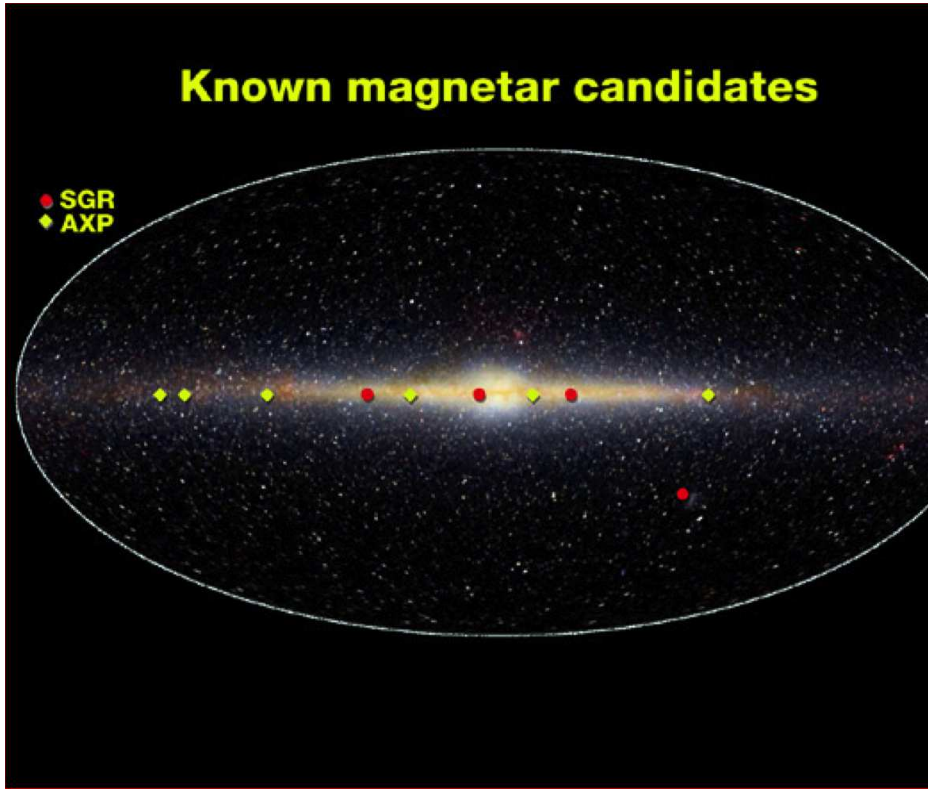
Can magnetars be quark stars?

- Measured electron-positron pairs can be explained if they are assumed to be emitted from bare *magnetized quark stars* **D.B. Melrose, R. Fock and D.P. Menezes, MNRAS (2006) 371, 204**:

- The dominant emission from bare strange stars is thought to be electronpositron pairs, produced through spontaneous pair creation (SPC) in a surface layer of electrons tied to the star by a superstrong electric field. The suppression of SPC is self-regulatory, and it adjusts so that SPC occurs at just the rate needed to replace electrons that escape.

- Treating pair emission from unmagnetized quark stars and assuming a FD distribution of electrons underestimates the suppression of SPC due to degeneracy, and overestimates the luminosity in pairs.





Courtesy pictures: C. Kouveliotou and Chengmin Zhang

Stability window

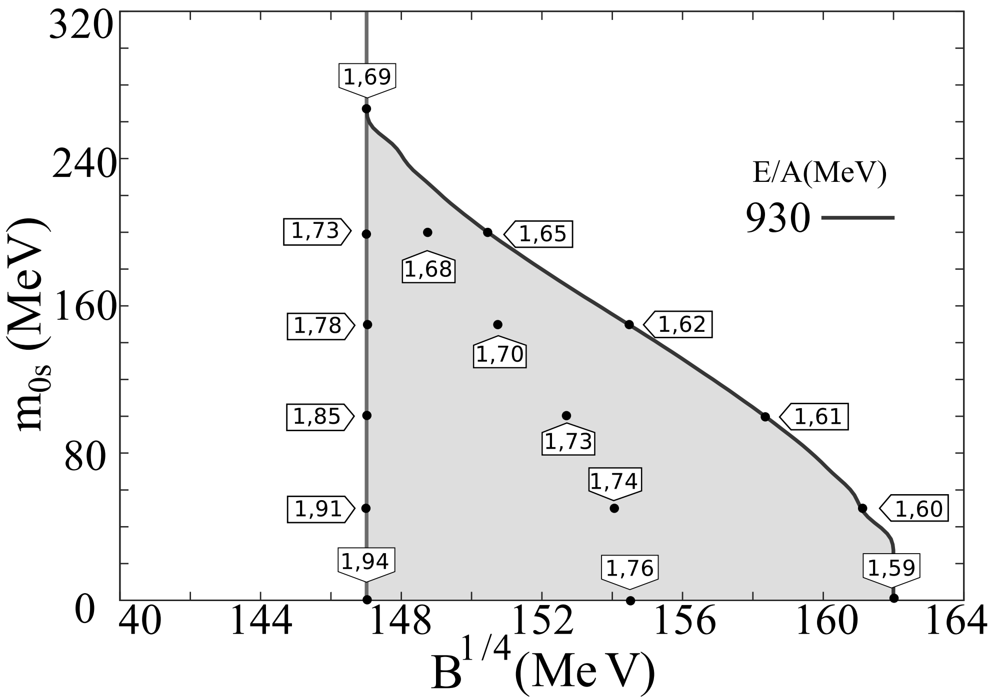
- Two-flavor quark matter (2QM) must be unstable - $\frac{E}{A} > 930$MeV (^{56}Fe binding energy)
- Three-flavor quark matter (SM) must be stable - $\frac{E}{A} \leq 930$MeV
- 2 quark models: MIT and NJL
- Zero (binding energy) and finite temperature (free energy)
- Unmagnetized and magnetized matter

For 2QM, $\mu_u = \mu_d$

For SM, $\mu_u = \mu_d = \mu_s$ (NOT β-equilibrium conditions!)

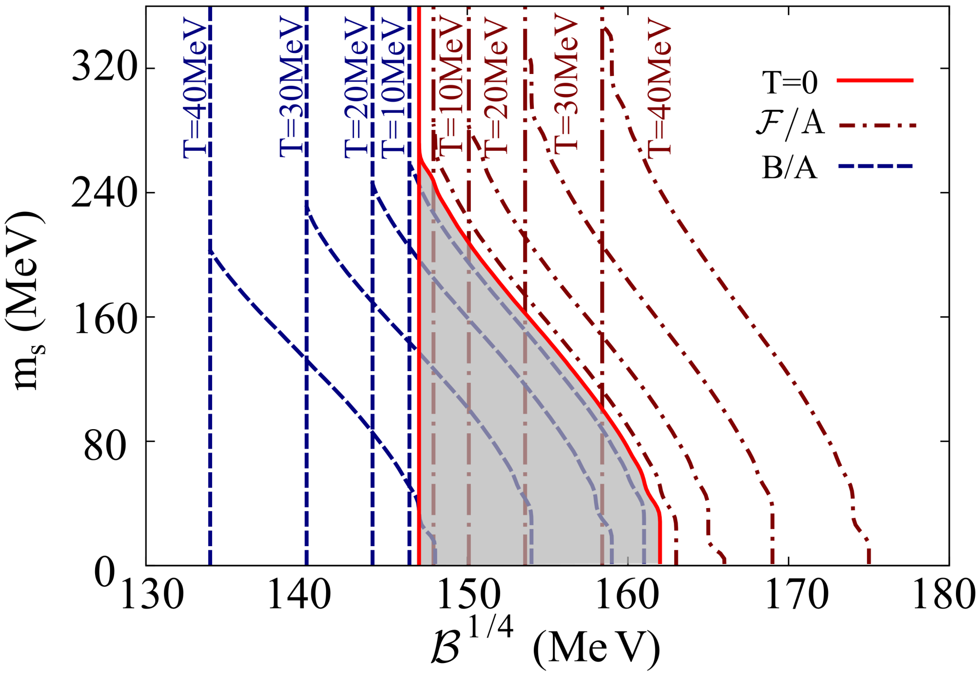
T=0 Results

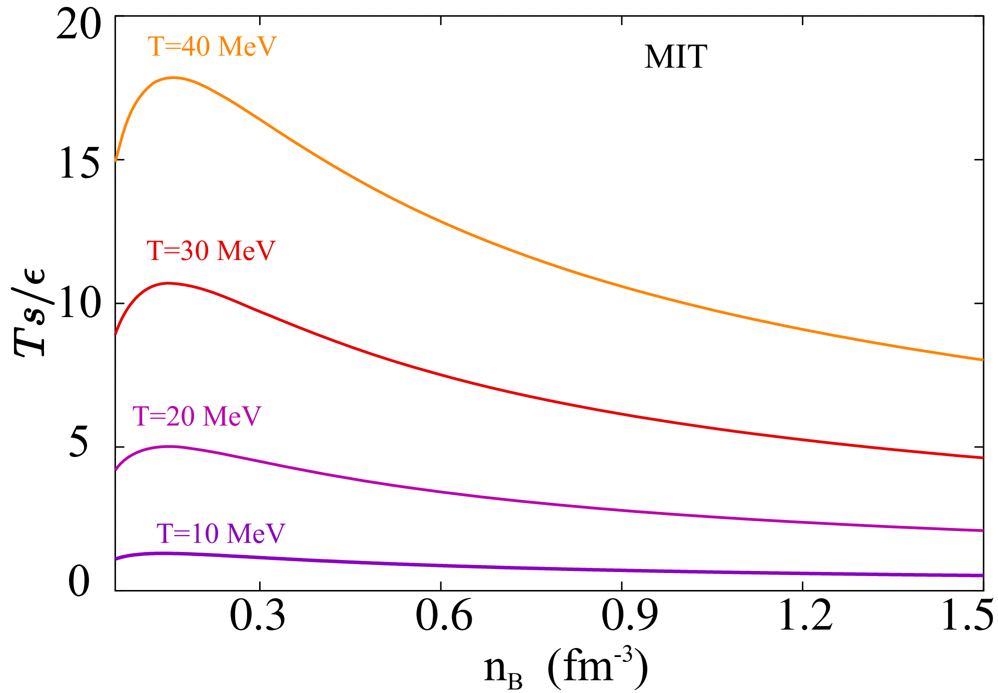
J.R. Torres and D.P.Menezes, Europhysics Letters, 101 (2013) 42003



Inside the flags we show the maximum masses ($M/M_\odot$) for the corresponding parameter sets inside the stability window.

Finite Temperature Results





At finite temperature, we should analyse the free energy density and NOT the binding energy.

J.R. Torres, D.P. Menezes and V. Dexheimer, Eur. Phys. Jour. C 73: 2569 (2013); arXiv:1303.5102 [astro-ph.HE]

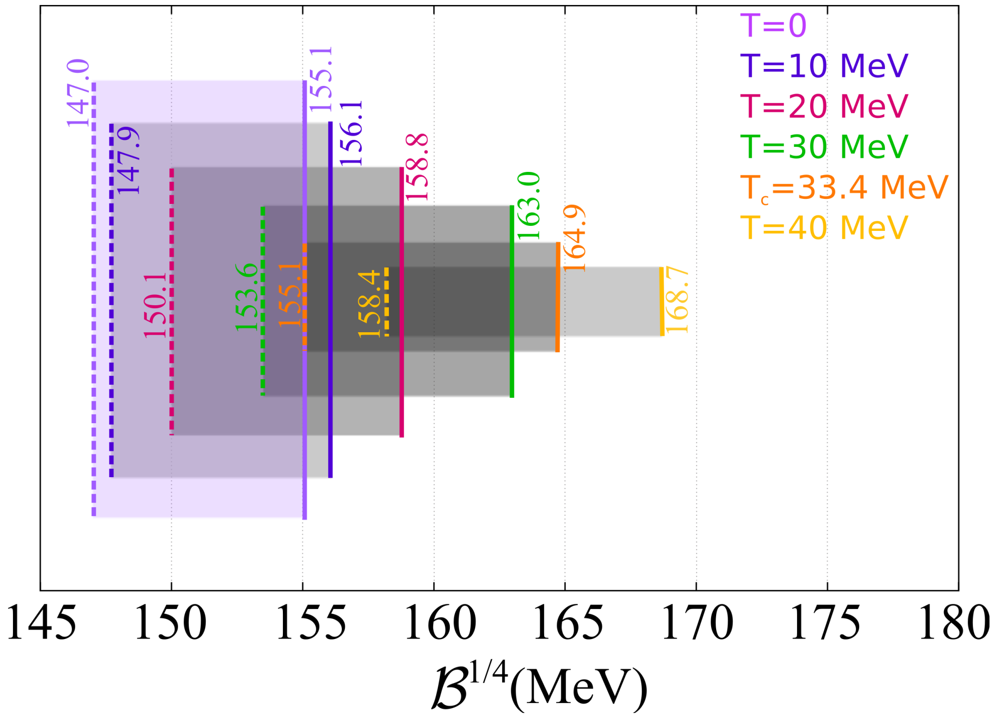
Influence of the magnetic fields - MIT

$$p = \sum_i \sum_\nu \frac{\gamma_i}{2\pi^2} |q_i| B \int dk_i \frac{k_i^2}{\sqrt{k_i^2 + \bar{m_i}^2}} (f_{+i} + f_{-i}) - \mathcal{B}, \tag{1}$$

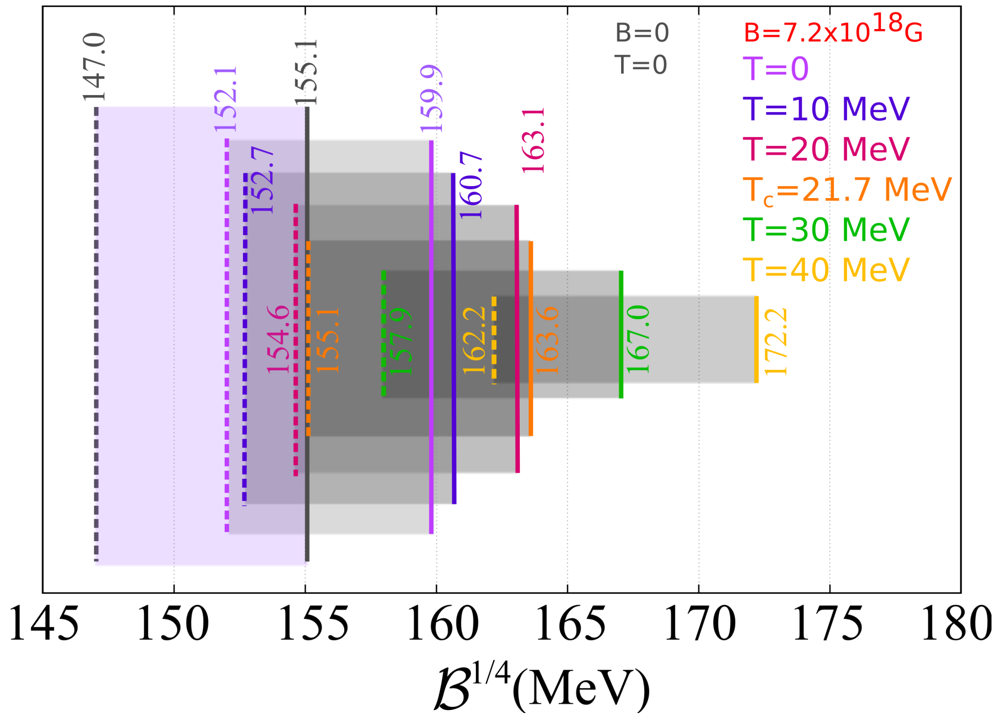
$$\epsilon = \sum_i \sum_\nu \frac{\gamma_i}{2\pi^2} |q_i| B \int dk_i \sqrt{k_i^2 + \bar{m_i}^2} (f_{+i} + f_{-i}) + \mathcal{B}, \tag{2}$$

$$\rho_B = \sum_i \frac{\rho_i}{3} = \frac{1}{3} \sum_i \sum_\nu \frac{\gamma_i}{2\pi^2} |q_i| B \int dk_i (f_{+i} - f_{-i}), \tag{3}$$

B is parallel to the z direction, $\bar{m}_i = \sqrt{m_i^2 + 2|q_i| B\nu}$, $\quad E_i = \sqrt{k_i^2 + \bar{m_i}^2}$



MIT $B = 0$



MIT $B = 7.2 \times 10^{18}$ G

NJL model + magnetic field

The NJL model allows a more realistic description of quark matter, as it contains chiral symmetry restoration/breaking.

$$\mathcal{L} = \bar{\psi}_f \left[\gamma_\mu \left(i\partial^\mu - q_f A^\mu\right) - \hat{m}_c\right] \psi_f \ + \ \mathcal{L}_{sym} \ + \ \mathcal{L}_{t'Hooft} \ + \ \mathcal{L}_{vec}, \qquad (4)$$

$$\mathcal{L}_{sym} \ = \ G \sum_{a=0}^{8} \left[(\bar{\psi}_f \lambda_a \psi_f)^2 + (\bar{\psi}_f i\gamma_5 \lambda_a \psi_f)^2\right] \ , \qquad (5)$$

$$\mathcal{L}_{t'Hooft} \ = \ -K \left\{\mathrm{det}_f \left[\bar{\psi}_f (1+\gamma_5)\psi_f\right] + \mathrm{det}_f \left[\bar{\psi}_f (1-\gamma_5)\psi_f\right]\right\} \ , \qquad (6)$$

$$\mathcal{L}_{vec} = -G_v (\bar{\psi}_f \gamma^\mu \psi_f)^2, \quad \tilde{\mu}_f = \mu_f - 2G_v \rho, \quad G_v = xG \qquad (7)$$

Notice there is another prescription in the literature.

- **Prescription 1 - Ruggieri, Sedrakian, Lugones, Malheiro, Providência, Blaschke**

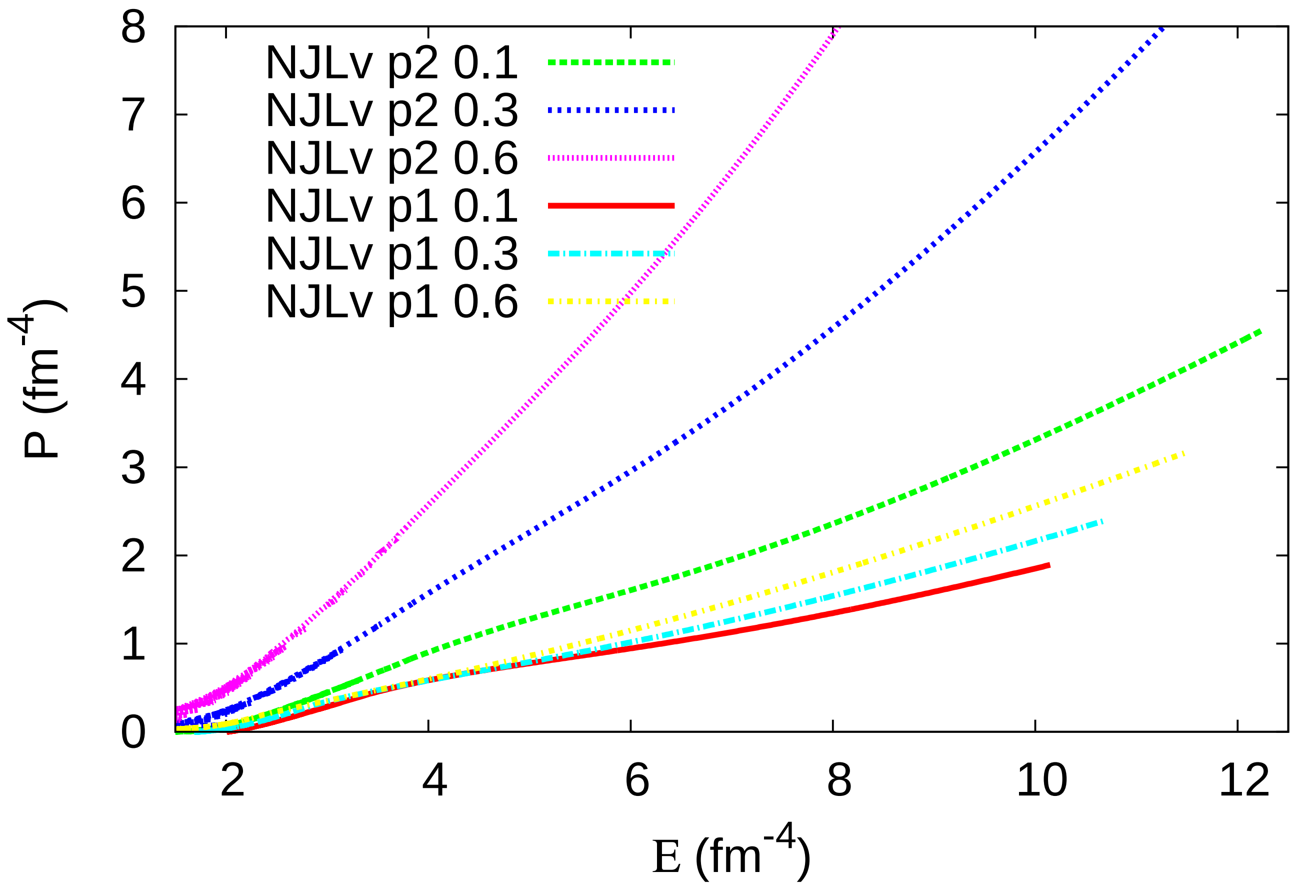
$$\tilde{\mu}_f = \mu_f - 2G_V\rho_f \quad f = u, d, s \tag{8}$$

$$P_f = \theta_u + \theta_d + \theta_s - 2G(\phi_u^2 + \phi_d^2 + \phi_s^2) + G_V(\rho_u^2 + \rho_d^2 + \rho_s^2) + 4K\phi_u\phi_d\phi_s \tag{9}$$

- **Prescription 2 - Weise, Di Toro, Sasaki, Fukushima, Hatsuda**

$$\tilde{\mu}_f = \mu_f - 2G_V\rho \quad \rho = \rho_u + \rho_d + \rho_s \tag{10}$$

$$P_f = \theta_u + \theta_d + \theta_s - 2G(\phi_u^2 + \phi_d^2 + \phi_s^2) + G_V(\rho_u + \rho_d + \rho_s)^2 + 4K\phi_u\phi_d\phi_s \tag{11}$$



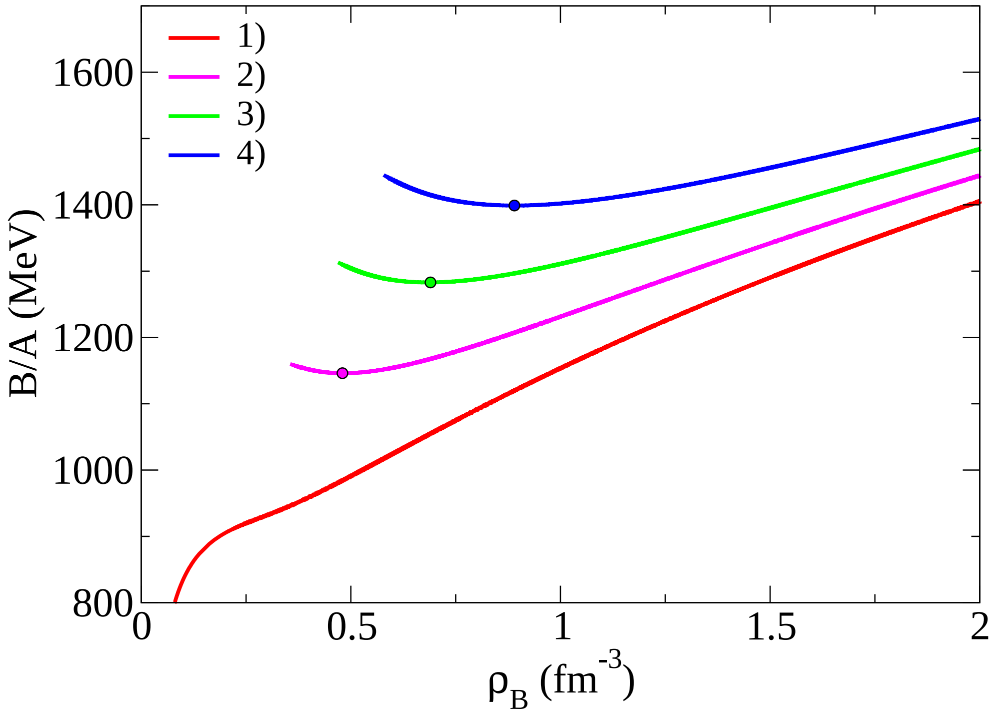
p1=prescription 1, p2=prescription 2 yields much harder EoS

Set	Group	Λ [MeV]	$G\Lambda^2$	$m_{u,d}$ [MeV]	$K\Lambda^5$	m_s [MeV]
1	SU(2)	664.3	2.06	5	N/A	N/A
2	SU(2)	587.9	2.44	5.6	N/A	N/A
3	SU(2)	569.3	2.81	5.5	N/A	N/A
4	SU(2)	568.6	3.17	5.1	N/A	N/A
5	SU(3)	602.3	1.835	5.5	12.36	140.7
6	SU(3)	631.4	1.835	5.5	9.29	135.7

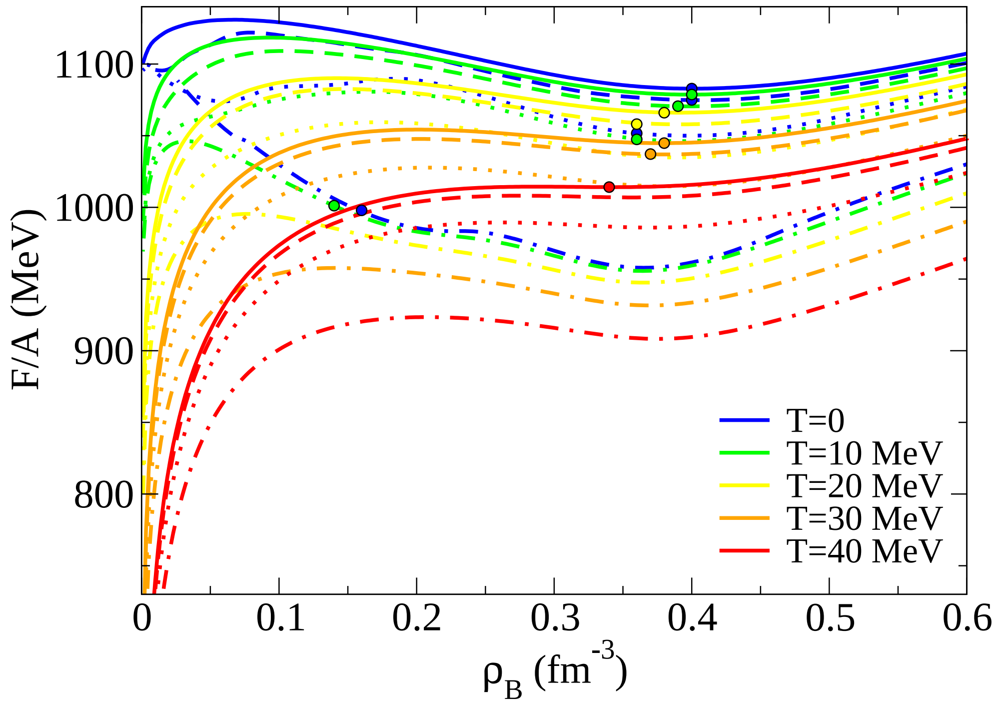
Parameters taken from M. Buballa, Phys. Rep. 407 (2005) 205

set 5 - Rehberg, Klevansky and Hüfner

set 6 - Hatsuda and Kunihiro



SU(2) T=0 $B = 0$ G



SU(3)

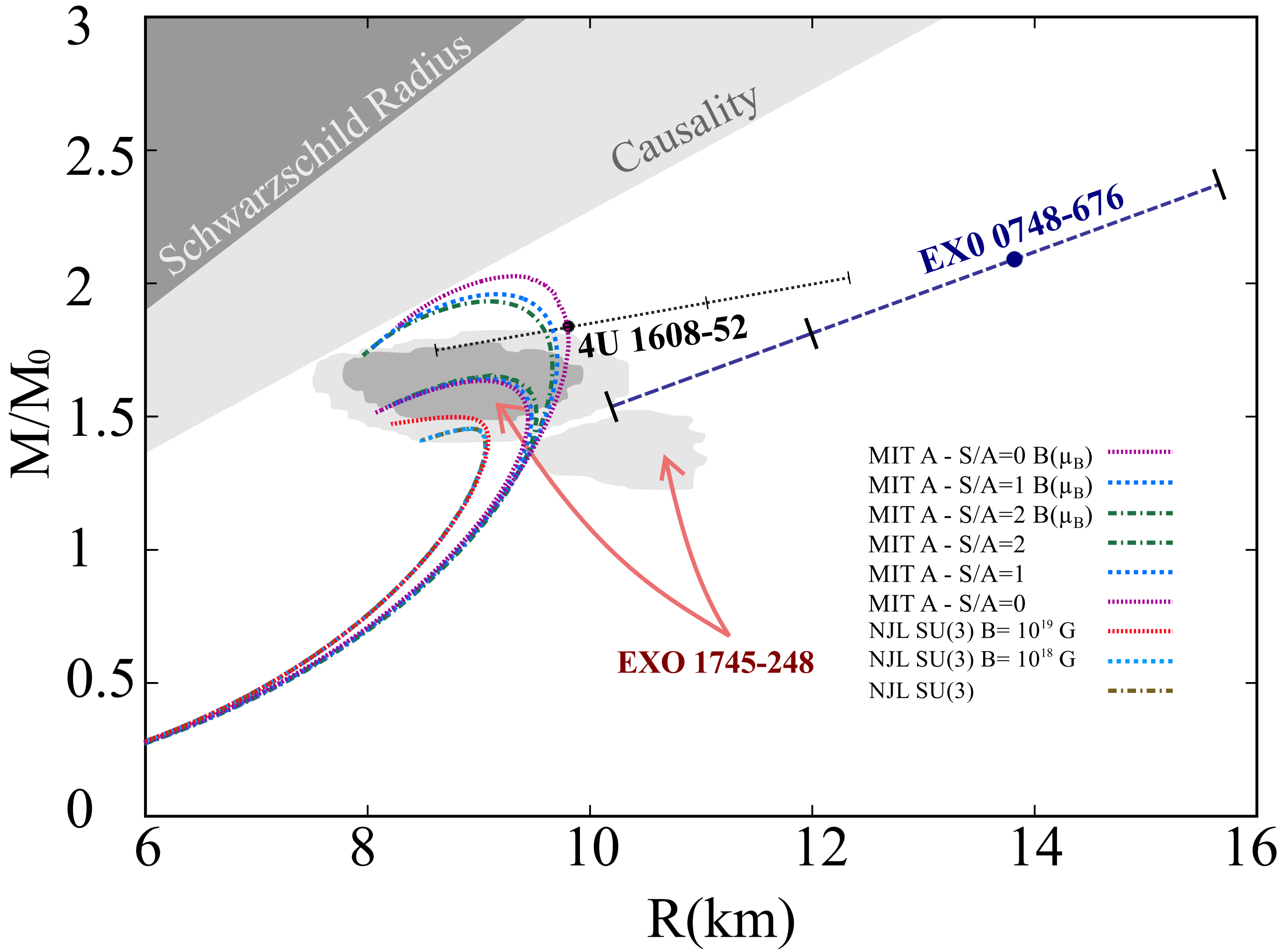
Full lines - $B = 1 \times 10^{18}$ G, dashed lines $B = 5 \times 10^{18}$ G, dotted lines $B = 1 \times 10^{19}$ G, dot-dashed lines $B = 2 \times 10^{19}$ G.

Strange matter hypothesis not always respected when quark matter is used to describe quark stars!

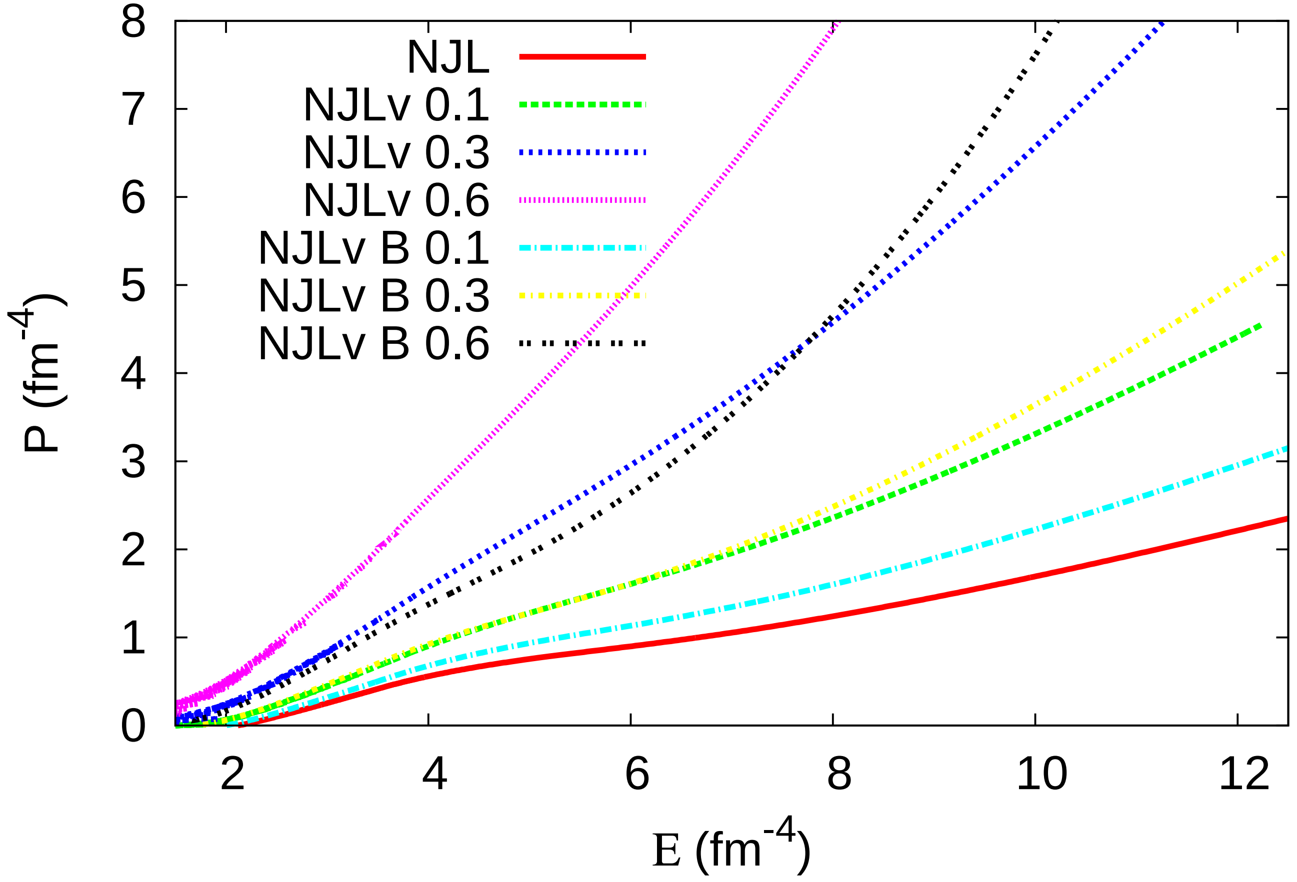
Properties of the stars

Model	$B^{1/4}$ MeV	S/A	B_c (G)	M_{max} ($M_\odot$)	R (km)	ϵ_c (fm^{-4})	T_c MeV
MIT	155	0	0	1.62	9.01	8.25	0
MIT	155	1	0	1.64	9.10	7.96	13.32
MIT	155	2	0	1.65	9.15	7.85	26.59
MIT	155	0	6.64×10^{18}	2.02	9.04	8.31	0
MIT	155	1	4.71×10^{18}	1.95	9.05	8.82	12.20
MIT	155	2	4.44×10^{18}	1.93	9.08	8.69	24.27
NJL	set 5	0	0	1.46	8.93	7.49	0
NJL	set 5	0	10^{18}	1.46	8.93	7.49	0
NJL	set 5	0	10^{19}	1.50	8.78	8.36	0
NJLv	set 6 / 0.1	0	10^{15}	1.41	8.29	8.96	0
NJLv	set 6 / 0.3	0	10^{15}	1.56	8.03	11.03	0
NJLv	set 6 / 0.5	0	10^{15}	1.95	9.22	8.21	0
NJLv	set 6 / 0.6	0	10^{15}	2.12	9.75	7.28	0

Radii always smaller than 11 Km!!

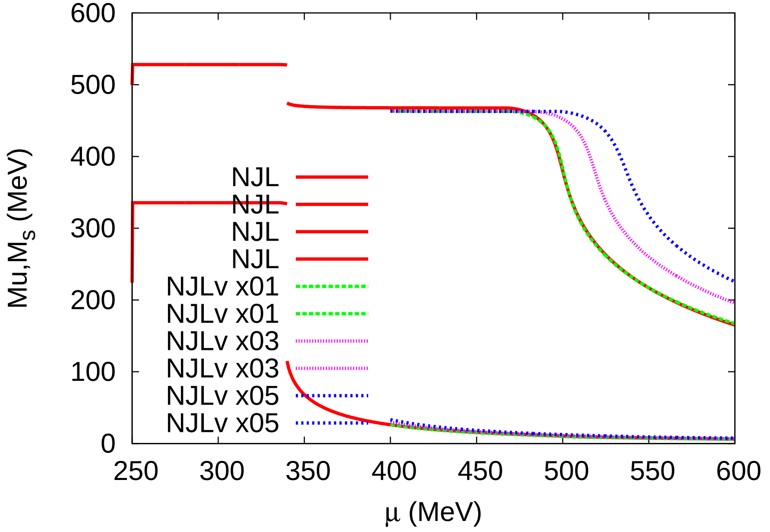


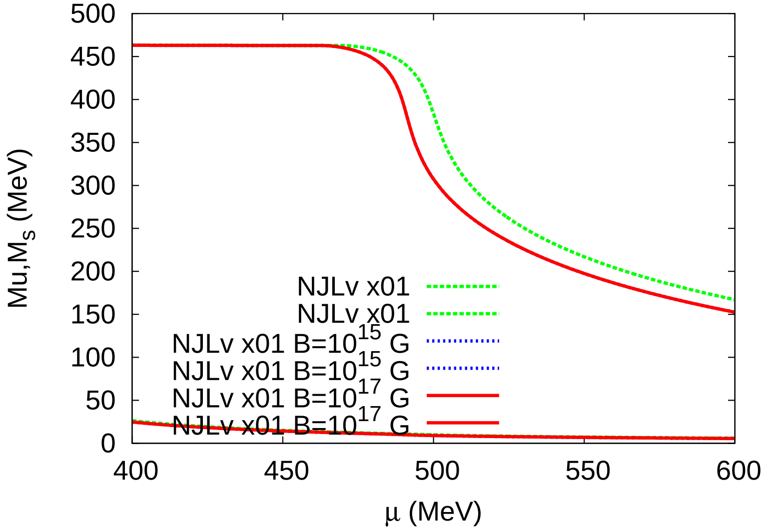
Also included lower and upper limits of the masses and radii of EXO 0748-676 and 4U 1608-52; shaded clouds refer to the 1σ and 2σ confidence ellipse of the results obtained in for the EXO 1745-248

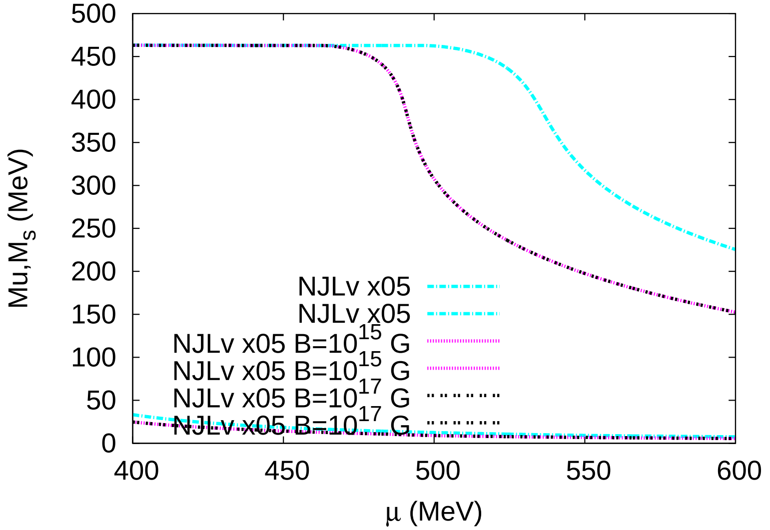


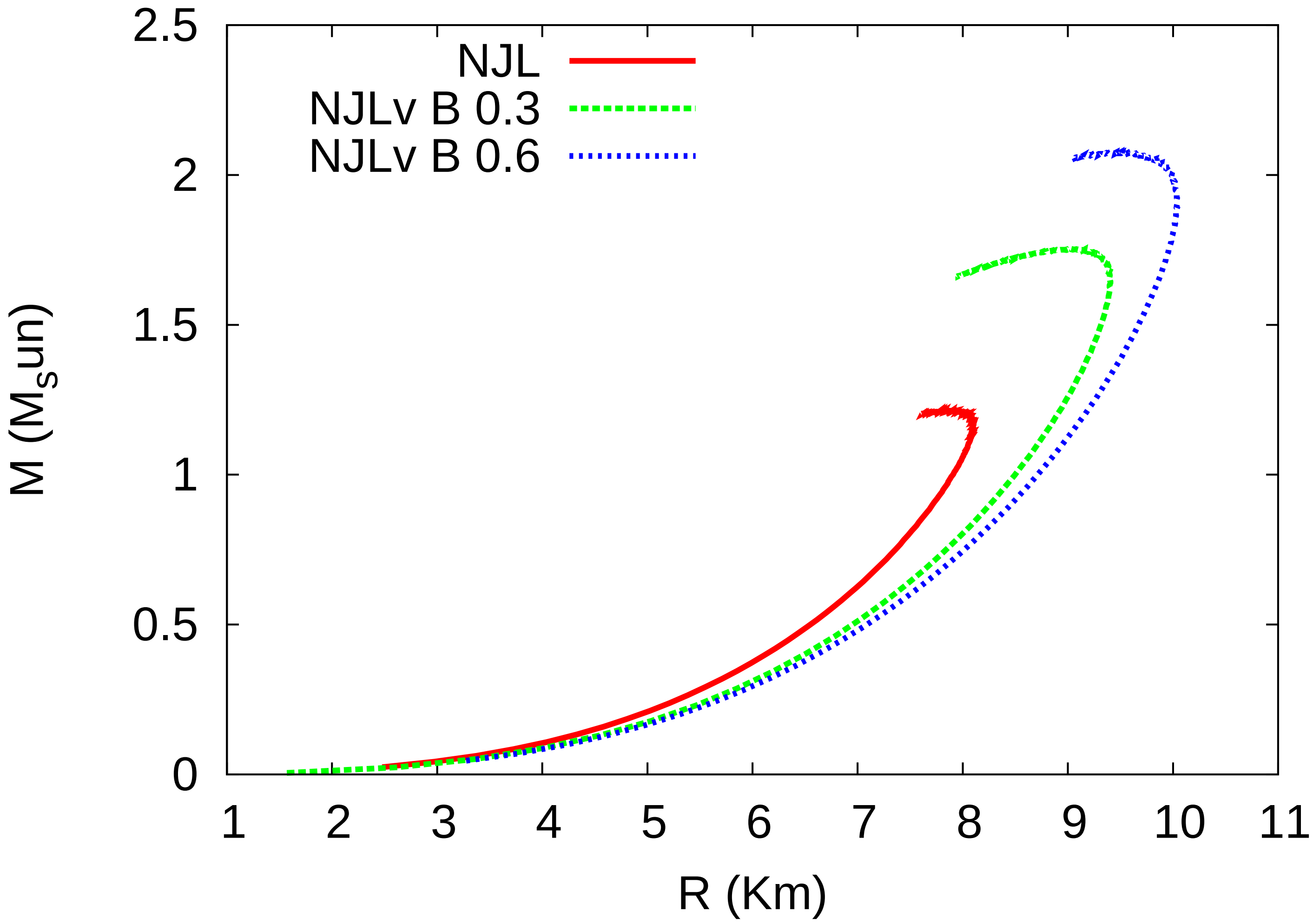
$B = 10^{15}$ **G throughout the star , generally B makes the EoS harder, but not with NJLv. Why?**

There is a competition between the magnetic field and the repulsive vector interaction









$B = 10^{15}$ **G throughout the star**

Hybrid Stars - no mixed phase

Hadronic matter - NLWM - GM1 parametrization

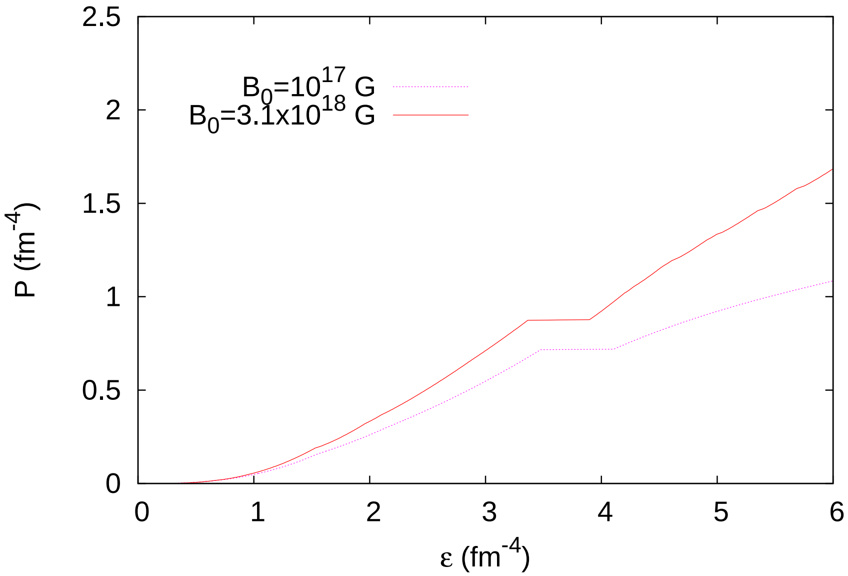
Quark matter - NJL model

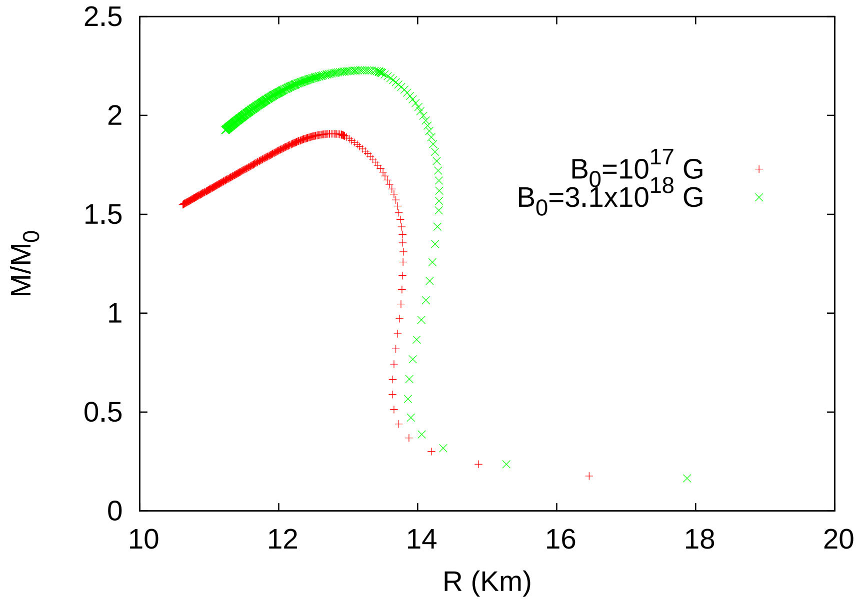
$$B\left(\frac{\rho}{\rho_0}\right) = 10^{15} + B_c\left\{1 - \exp\left[-\beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}\right]\right\} \tag{12}$$

Fast decay: $\gamma = 3.00$ and $\beta = 0.02$

Slow decay: $\gamma = 2.00$ and $\beta = 0.05$

Typical results for EOS and M x R curves (slow decay).





Magnetic Field	FAST		SLOW	
	$M_{max}(M_0)$	R (Km)	$M_{max}(M_0)$	R (Km)
$B_0 = 10^{17}\ G$	1.91	12.78	1.91	12.78
$B_0 = 3.1 \times 10^{18}\ G$	2.25	12.76	2.23	13.24

MIT + B - anisotropic EOS

$$\begin{aligned}\mathcal{L} &= \left[\bar{\Psi}_q \left(i\gamma^\mu \partial_\mu - e_q \gamma^\mu A_\mu - m_q\right) \Psi_q - \mathcal{B}\right] \Theta_V \\ &- \frac{1}{16\pi} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}_l \left(i\gamma^\mu \partial_\mu - e_l \gamma^\mu A_\mu - m_l\right) \Psi_l,\end{aligned} \tag{13}$$

$\mathcal{B} = (154 \text{ MeV})^4$, chosen from the stability window analysis

$$
\begin{aligned}
M &= -\frac{\partial \Omega}{\partial B} = \frac{P_{m_{\parallel}}}{B} - \sum_{i,\nu} \frac{\gamma_i}{2\pi^2} Q_{e_i}^2 e^2 B \nu \int \frac{1}{\sqrt{k_i^2 + \bar{m}_i^2}} \\
&\times (f_{+_i} + f_{-_i}) dk,
\end{aligned} \tag{14}
$$

$$
P_{m_{\perp}} = P_{m_{\parallel}} - MB, \quad \bar{m}_i = \sqrt{m_i^2 + 2|Q_{e_i}| eB\nu} \tag{15}
$$

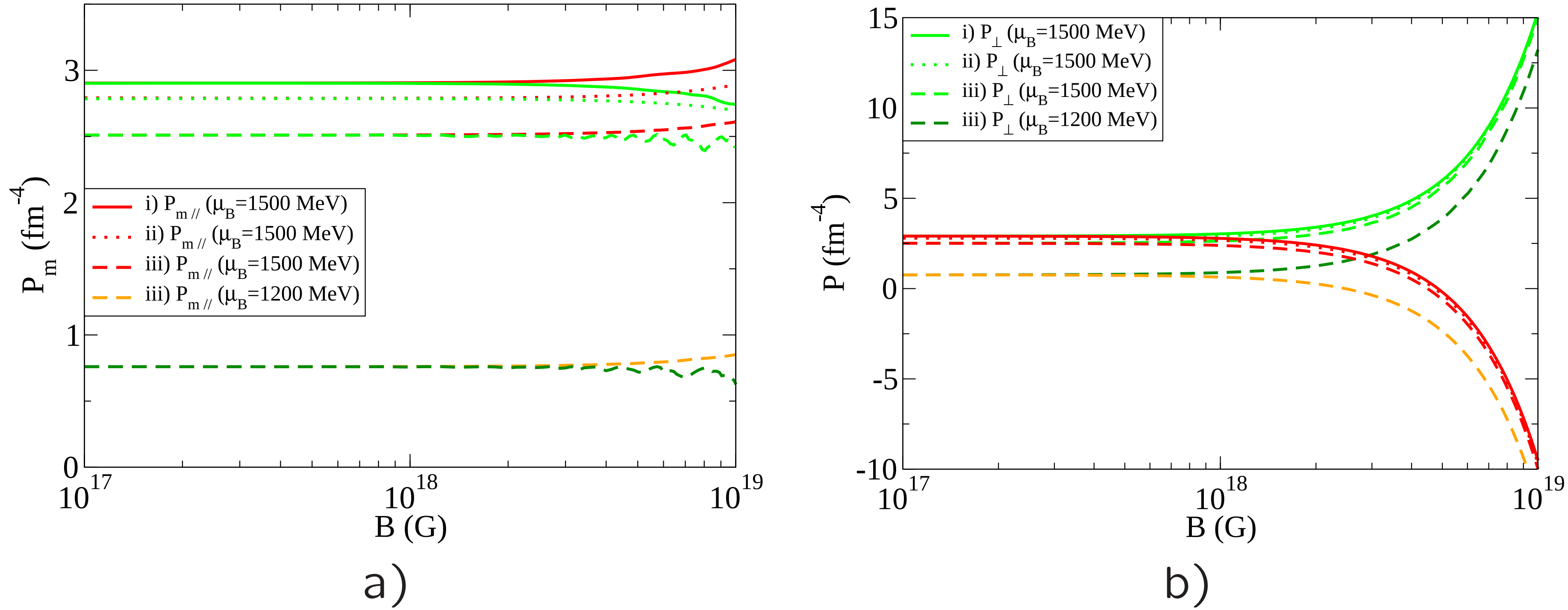
$$
\epsilon = \epsilon_m + \frac{B^2}{8\pi}, \quad P_{\perp} = P_{m_{\perp}} + \frac{B^2}{8\pi}, \quad P_{\parallel} = P_{m_{\parallel}} - \frac{B^2}{8\pi}, \tag{16}
$$

$$
B(\mu_B) = 10^{15} + B_c \left[1 - e^{b \frac{(\mu_B - 938)^a}{938}} \right], \quad a = 2.5, b = -4.08 \times 10^{-4} \tag{17}
$$

$$\frac{S}{A} = \frac{s}{\rho_B} = \frac{\epsilon + P_{\|} - \mu_B \rho_B}{T \rho_B}, \quad Y_l = \frac{\sum_i Q_{l i} \rho_i}{\rho_B} \tag{18}$$

We consider three snapshots of the time evolution of a quark star in its first minutes of life:

- $s/\rho_B = 1$, $Y_l = 0.4$,
- $s/\rho_B = 2$, $\mu_{\nu_l} = 0$,
- $s/\rho_B = 0$, $\mu_{\nu_l} = 0$.



Parallel (red/orange lines) and perpendicular (green/dark green lines) pressures. $B^2/8\pi$ a) not included; b) included

The inclusion of anomalous magnetic moments do not modify the results qualitatively

V. Dexheimer, D.P. Menezes and M. Strickland, arXiv: 1210.4526 [nucl-th].

Conclusions

- The Bodmer-Witten conjecture is not always respected when quark matter is used to describe quark stars! Results have to be taken with care.

- Strong magnetic fields modify quark star masses.

- The MIT bag model for a $\mathcal{B}^{1/4} = 154/155$ MeV obtained from an investigation of the adequate stability window cannot reproduce the very massive neutron stars recently detected, not even if very intense magnetic fields are considered.

- The same holds for the NJL model, but not for the NJLv model, as far as a large interaction is enforced. This is also true for $B = 0$.

- Hybrid stars built with quark matter described by the NJL model can be very massive in contrast with calculations where the MIT model is used. The NJLv model can make them even more massive.

- The level of pressure anisotropy at stage i) is relatively small $P_{\parallel}/P_{\perp} \simeq$ 0.85 for the lower value of the magnetic field. We can then use the isotropic TOV equations which assume $P_{\perp} = P_{\parallel}$.

- For the larger value of the magnetic field studied, the level of pressure anisotropy is quite large with $P_{\parallel}/P_{\perp} \simeq 0.4$.

- For magnetic fields of the order of 10^{15} G, anisotropy is not a problem.

- At high values of the magnetic field one should solve Einstein's equations in an axisymmetric metric which is determined self-consistently from the axisymmetric energy-momentum tensor for the star. Numerical solution for the axisymmetric case is needed and we are currently working towards this goal.

Collaboration with

- Constança Providência (Coimbra, Portugal),
- Verônica Dexheimer (Kent U/USA), Mike Strickland (Kent U/USA),
- Norberto Scoccola (Tandar/Argentina)
- Luiz Rafael Benito Castro (post doc/UFSC),
- PhD students: Rudiney Hoffman Casali (UFSC), James Rudinei Torres (UFSC), Márcio Ferreira (Coimbra,Portugal)

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Thank you!