$2\,M_\odot$ hybrid stars from metastable hadronic stars

Constança Providência

collaborators

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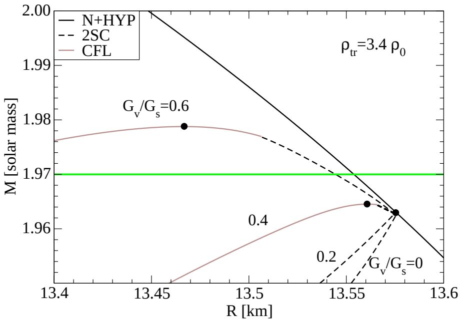
Motivation

- Will the nucleation forbid the appearance of QM in $2M_\odot$ neutron stars?
- Which constraints are set by the existence of QM in a NS?

Motivation

- Bonnano & Sedrakian, A&A539, A16 (2012)
  - *Stable configurations are obtained with $M \geq 1.97\ M_\odot$ including hyper-nuclear and quark matter in color superconducting state if the equation of state of nuclear matter is stiff above the saturation density*
  - NL3 and su(3) NJL including color superconductivity



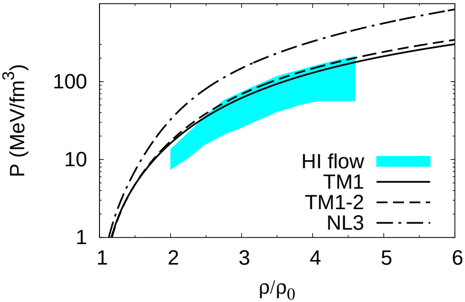
Outline

- EOS: hadron and quark phases
- Hadron-quark phase transition
- Including nucleation
- Discussion

Framework

Hadronic Matter

- Hadronic matter: NL3, TM1, TM1-2
  - behaviour at large ρ
- Heavy ion flow data constraints



- Effect of the inclusion of hyperons

Framework

Quark matter

- su(3) NJL quark model

$$\mathcal{L}_{NJL} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - \hat{m})\psi + G_S \sum_{a=0}^{8}[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2]$$
$$- K\left\{\det{}_f[\bar{\psi}(1+\gamma_5)\psi] + \det{}_f[\bar{\psi}(1-\gamma_5)\psi]\right\}$$
$$- G_V \sum_{a=0}^{8}[(\bar{\psi}\gamma_{\mu}\lambda_a\psi)^2 + (\bar{\psi}\gamma_5\gamma_{\mu}\lambda_a\psi)^2]$$

- no color superconductivity
- vector term contribution

Framework

Quark matter: su(3) NJL quark model

- Total pressure

$$p = \sum_{i=u,d,s} \int_{k_{Fi}}^{\Lambda} \frac{dk k^2}{2\pi^2} |\epsilon_i| - 2G_s \sum_{i=u,d,s} \sigma_i^2$$
$$+ 4K\sigma_u\sigma_d\sigma_s + 2G_V \sum_{i=u,d,s} n_i^2 - p_0 - B^* + \sum_{l=e^-,\mu^-} p_l \, ,$$

- vector term, extra effective bag parameter
  - $B^* \rightarrow$ defines hadron-quark phase transition (Plagiara&Schaffner-Bielich2008)
  - with vector contribuition $\rightarrow$ stiffer quark EOS

Hadron-quark matter transition

Gibbs criteria for phase equilibrium

- time scale of the deconfinement transition is determined by the strong interaction
- quark flavor must be conserved during the deconfinement transition
- Q^* phase: the deconfined quark matter with flavor content equal to that of the β-stable hadronic phase at the same pressure and temperature.

Hadron-quark matter transition

Gibbs criterion

- Metastable phase: starts at the transition point defined by Gibbs criterion

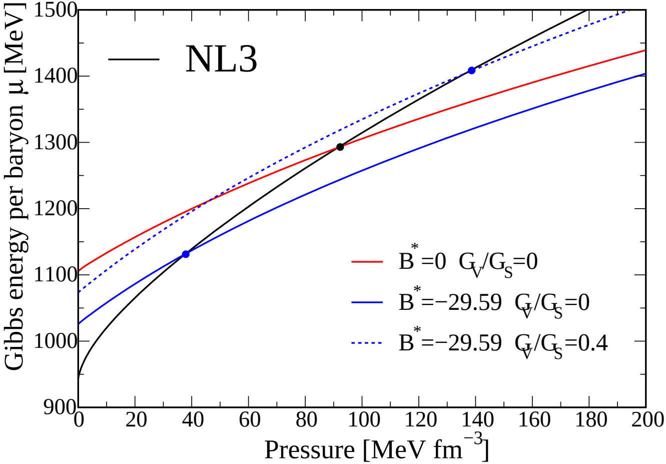
$$\mu_H = \mu_Q \equiv \mu_0 \ , \quad P_H(\mu_0) = P_Q(\mu_0) \equiv P_0 \ ,$$

$$\mu_H = \frac{\epsilon_H + P_H}{n_H} \ , \quad \mu_Q = \frac{\epsilon_Q + P_Q}{n_Q}$$

- central pressure $P > P_0$: hadronic phase is metastable $\rightarrow$ stable quark matter as result of a nucleation process

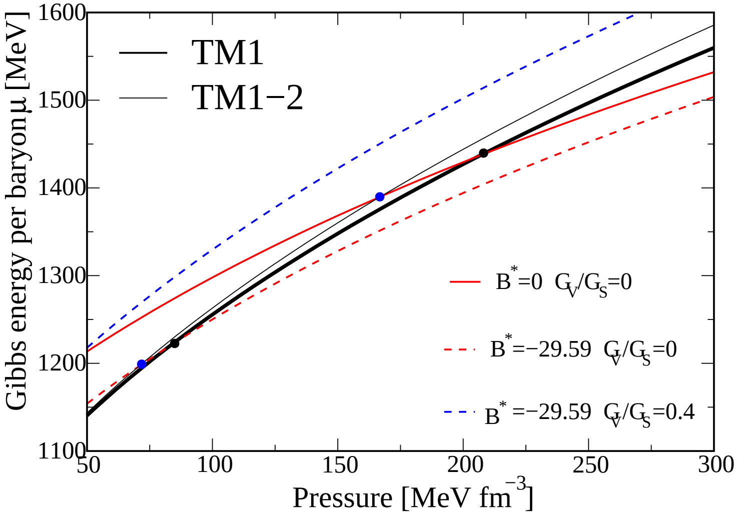
Hadron-quark matter transition

NL3 - effect of B^* and G_V



Hadron-quark matter transition

TM1



Quantum nucleation

Lifshitz& Kagan 1972,Iida& Sato 1998, Bombaci et al. 2004

- if $P > P_0 \rightarrow$ formation of Q^* phase
- Free energy difference between system with/without Q^* droplet

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

- Curvuture and Coulomb effects are negleted

Critical mass

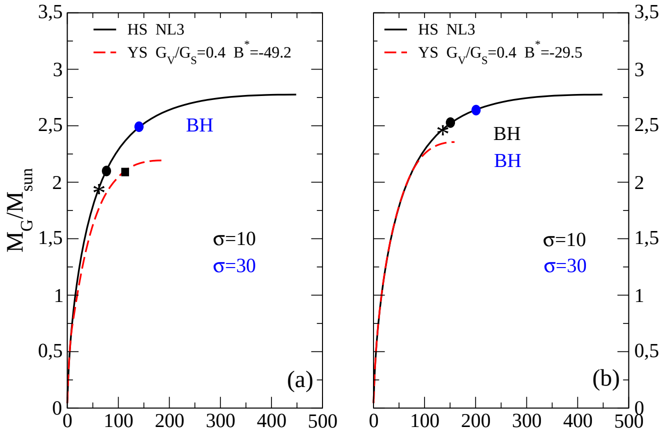
Lifshitz& Kagan 1972,Iida& Sato 1998, Bombaci et al. 2004

- WKB gives for quantum nucleation time

$$\tau_q = (\nu_0 p_0 N_c)^{-1} \ ,$$

- p_0: probability of tunneling
- $N_c \sim 10^{48}$: number of nucleation centers in $r \leq R_{nuc} \sim 100$ m
- ν_0: oscillation frequency of the drop in $U(\mathcal{R})$
- Critical mass M_{cr}: gravitational mass of cold and deleptonized of the metastable hadronic star with $\tau \sim$ 1yr.

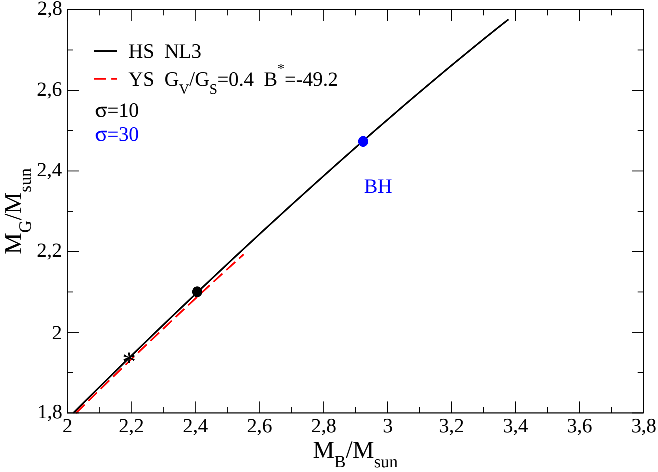
Star evolution



- Final configuration is not a blackhole if
  - G_V is strong enough: stiff quark EOS
  - B^* allows a hadron-quark phase transition a low enough ρ
- if $B^* > -49.2$ MeV/fm^3: transition to BH

Star evolution

Surface energy effect



- Evolution of a star occurs along a vertical line: constant baryonic mass

Final configuration: surface energy effect

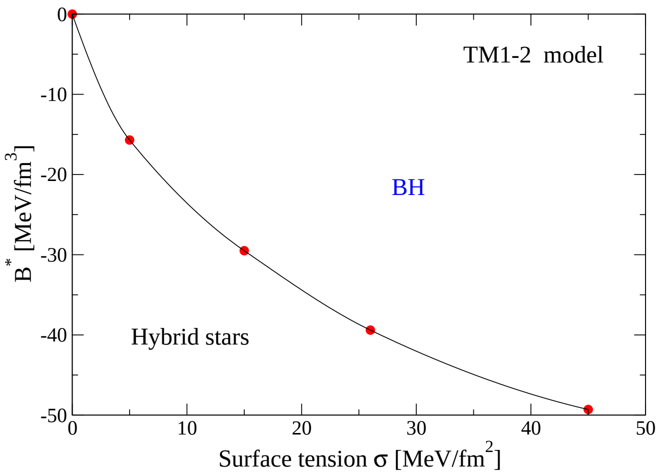
NL3+NJL

- Final configuration: hybrid stars with a quark core
- B^*=-49.23 (MeV/fm^3) , $G_V/G_S = 0.4$
- $M(P_0) = 1.92 M_\odot$

NL3	σ (MeV/fm^2)	M_{cr} $(M_\odot)$	M_{cr}^b $(M_\odot)$	M_{fin} $(M_\odot)$	M_{max}^{YS} $(M_\odot)$
	5	2.00	2.27	1.99	2.19
	10	2.09	2.40	2.08	2.19
	15	2.20	2.54	2.18	2.19
	30	2.45	2.89	BH	2.19

Stable final configurations

Surface energy vs B^*



Final configuration

Hybrid star or blackhole

- TM1+NJL: hybrid star with a mixed phase core, $G_V = 0$

σ $\left(\frac{\text{MeV}}{\text{fm}^2}\right)$	B^* $\left(\frac{\text{MeV}}{\text{fm}^3}\right)$	P_0 $\left(\frac{\text{MeV}}{\text{fm}^3}\right)$	$M(P_0)$ $(M_\odot)$	M_{cr} $(M_\odot)$	M_{fin} $(M_\odot)$	M_{max}^{YS} $(M_\odot)$
5	0	206.71	2.08	2.09	BH	1.97
5	-15.78	147.53	2.01	2.03	BH	1.95
10	-29.59	82.89	1.76	1.88	1.87	1.92
30				1.93	BH	1.92
20	-39.46	37.92	1.31	1.85	1.84	1.90
25				2.03	BH	1.90
30	-49.33	26.75	1.11	1.36	1.35	1.88
50				1.87	1.86	1.88
70				2.11	BH	1.88

Final configuration

Hybrid star or blackhole

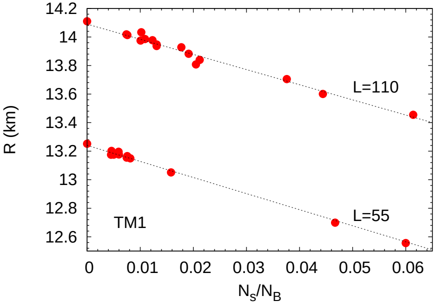
TM1-2+NJL: Hybrid stars have a mixed phase core, $G_V = 0$

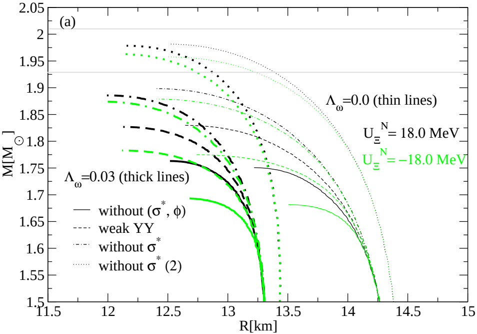
σ $\left(\frac{\text{MeV}}{\text{fm}^2}\right)$	B^* $\left(\frac{\text{MeV}}{\text{fm}^2}\right)$	P_0 $\left(\frac{\text{MeV}}{\text{fm}^2}\right)$	$M(P_0)$ $(M_\odot)$	M_{cr} $(M_\odot)$	M_{fin} $(M_\odot)$	M_{max}^{YS} $(M_\odot)$
5	0	166.69	2.12	2.14	BH	2.05
5	-15.78	120.30	2.00	2.03	1.86	2.02
8				2.05	BH	2.02
10	-29.59	70.30	1.73	1.87	1.86	1.99
15				1.93	1.92	1.99
20				2.00	BH	1.99
25	-39.46	35.93	1.31	1.94	1.95	1.97
30				2.04	BH	1.97
45	-49.33	26.39	1.12	1.92	1.92	1.94
50				2.03	BH	1.94

Effect of the strangeness

Hadronic EOS with hyperons

- Include hyperons in the RMF
- $g_{\omega H}$, $g_{\rho H}$, and $g_{\phi H}$ are determined from SU(6) symmetry
- $U_\Lambda = -28$MeV, $U_\Sigma = 30$ MeV, $U_\Xi = 18$ MeV, $g_{\sigma^* Y} = 0$





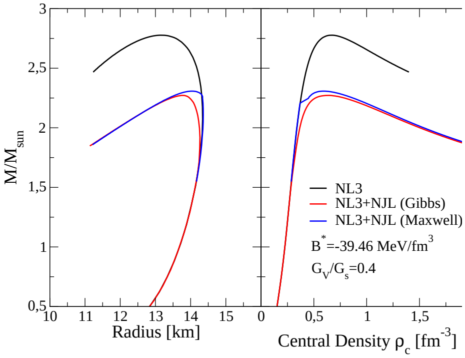
Effect of the strangeness

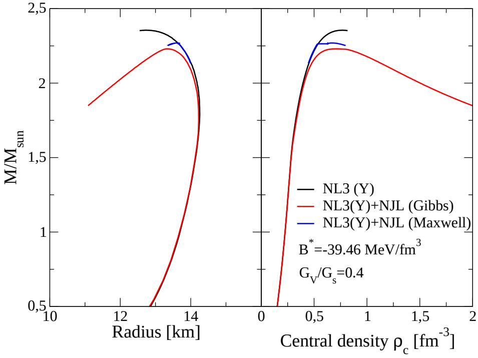
- $B^* = -39.46 \left(\text{MeVfm}^3\right)$

Model	σ $\left(\frac{\text{MeV}}{\text{fm}^2}\right)$	P_0 $\left(\frac{\text{MeV}}{\text{fm}^3}\right)$	$M(P_0)$ $(M_\odot)$	M_{cr} $(M_\odot)$	M_{fin} $(M_\odot)$	M_{max}^{YS} $(M_\odot)$
NL3						
N	5	97.87	2.27	2.33	BH	2.27
N	30			2.57	BH	2.27
NY	29	21.63	1.19	2.22	2.20	2.23
TM1-2						
N	25	35.93	1.31	1.94	1.95	1.97
N	30			2.04	BH	1.97
NY	11.5	14.16	0.925	1.83	1.82	1.90

Gibbs vs Maxwell construction

- Finite size effects and Coulomb interaction: close to Maxwell const $\gtrsim$ 50 MeV/fm^2 (Endo et al, PTP 2006, Maruyama et al PRD76 (2007))





Discussion

Very stiff hadronic EOS

NL3, very stiff hadronic EOS, Hibrid stars with quark core

- $G_V = 0$
  - nucleation $\rightarrow$ BH if $|B^*| \leq |B_c^*|$
  - if $|B^*| > |B_c^*|$, nucleation to stable hybrid stars but $M < 2M_\odot$
- $G_V > G_{Vc}$
  - hadron-quark transition at larger ρ
  - nucleation $\rightarrow$ BH if $|B^*| \leq |B_c^*|$
  - if $|B^*| > |B_c^*|$, nucleation to stable hybrid stars and $M \gtrsim 2M_\odot$
  - however if σ too large $\rightarrow$ BH

TM1: stiff hadronic EOS, hybrid stars with mixed phase

- $G_V < 0.2$
  - quark EOS too stiff
  - no hadron-quark transition or at too large ρ
- $G_V = 0$
  - if $|B^*| > |B_c^*|$ nucleation to stable hybrid stars (mixed phase in core)
  - Maximum M depends on σ
  - TM1 with $\sigma \lesssim 5 - 50$MeV/fm^2, $M_{max} \sim 1.92 - 1.88 M_\odot$
  - TM1-2 with $\sigma \lesssim 5 - 15$MeV/fm^2, $M_{max} \sim 2.02 - 1.99 M_\odot$

Conclusions

- Not all stable hybrid stars are populated after nucleation!
- Hadronic EOS with hyperons
  - if repulsive YY interaction included only slightly smaller maximum mass (more information about hyperon-hyperon interaction needed!)
- Could nucleation occur at finite T to massive stable hybrid stars? needs checking!
- HI flow constraints $\rightarrow \sim 2 - 2.1 M_\odot$ but not 2.4 $M_\odot$
- How much confidence on HI constraints? More precise high density constraints are need!
- Better knowledge of surface tension σ