NJL hybrid stars & the recent $2M_{\odot}$ pulsars

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Outline of the talk:

1. NJL hybrid stars & the recent $2M_{\odot}$ pulsars

Lenzi & Lugones; ApJ. 759, 57 (2012)

2. Discriminating compact stars through GWs of pulsation modes

Flores & Lugones; arXiv:1310.0554

3. Few words about surface tension.

Lugones, Grunfeld & Ajmi, arXiv:1308.1452

1. NJL hybrid stars & the recent $2M_{\odot}$ pulsars

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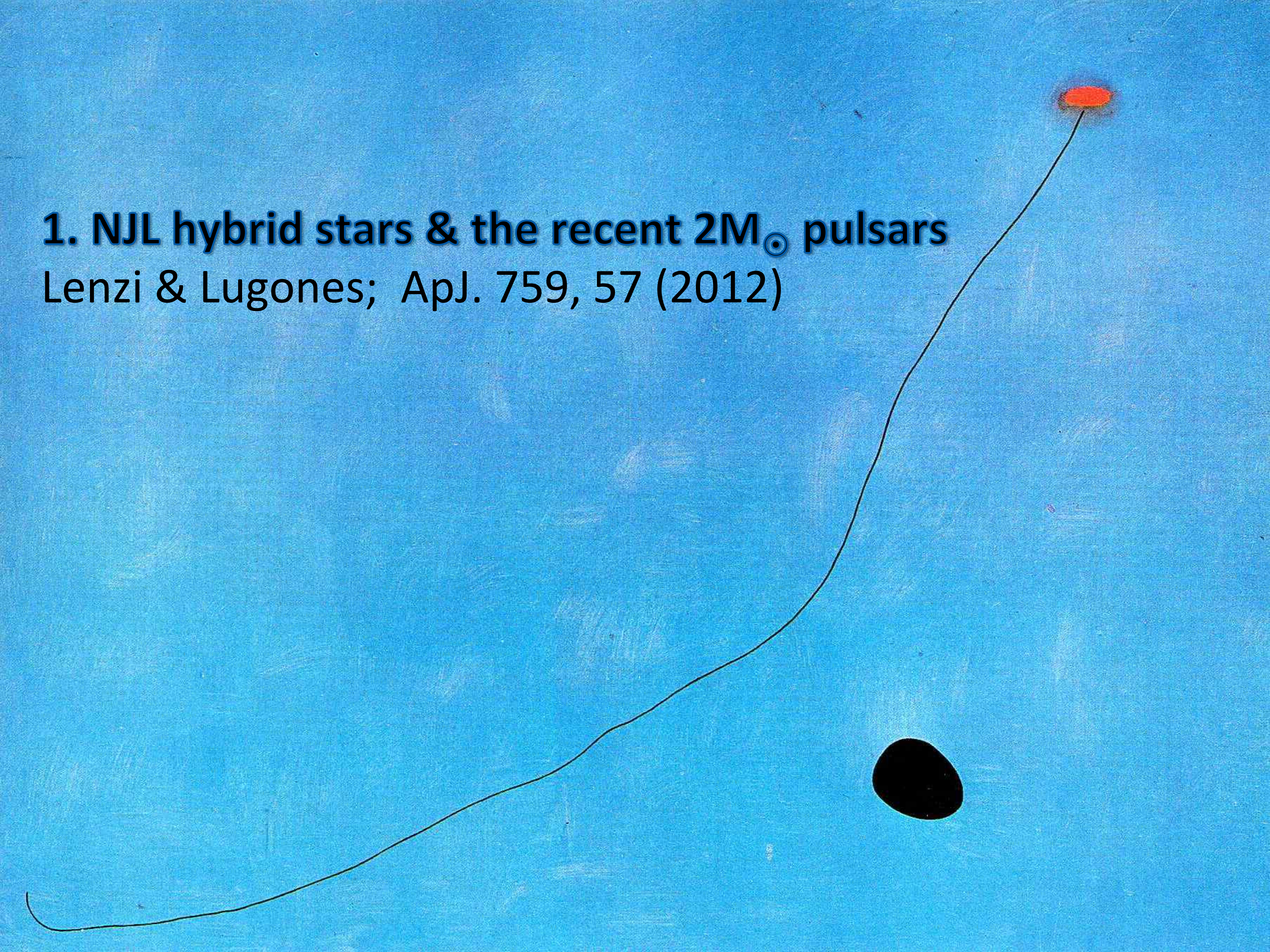


Hadronic matter

Relativistic mean field model with neutrons, protons and electrons (GM1, TM1 & NL3 parametrizations).

$$\mathcal{L} = \sum_B \bar{\psi}_B (i\gamma_\mu \partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - \tfrac{1}{2} g_{\rho B}\gamma_\mu \boldsymbol{\tau}\cdot\boldsymbol{\rho}^\mu)\psi_B + \tfrac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \tfrac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \tfrac{1}{2} m_\omega^2 \omega_\mu \omega^\mu$$
$$- \tfrac{1}{4}\boldsymbol{\rho}_{\mu\nu}\cdot\boldsymbol{\rho}^{\mu\nu} + \tfrac{1}{2} m_\rho^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu - \tfrac{1}{3} b m_n (g_\sigma \sigma)^3 - \tfrac{1}{4} c (g_\sigma \sigma)^4 + \sum \bar{\psi}_\lambda (i\gamma_\mu \partial^\mu - m_\lambda)\psi_\lambda .$$

Coupling Constants for the Parameterizations GM1 (Glendenning & Moszkowski 1991), TM1 (Sugahara & Toki 1994), and NL3 (Lalazissis et al. 1997)

Set	GM1	TM1	NL3
m_σ (MeV)	512	511.198	508.194
m_ω (MeV)	783	783	782.501
m_ρ (MeV)	770	770	763
g_σ	8.91	10.029	10.217
g_ω	10.61	12.614	12.868
g_ρ	8.196	9.264	8.948
b	0.002947	−0.001506	0.002055
c	−0.001070	0.000061	−0.002651
$M_{\rm max}$	2.32	2.18	2.73

Notes. $M_{\rm max}$ is the maximum mass of a pure hadronic star for matter composed of nucleons and electrons.

Quark matter

QUARK MATTER: SU(3) NJL model with scalar–pseudoscalar, isoscalar–vector, and 't Hooft six-fermion interactions.

$$
\begin{aligned}
\mathcal{L}_Q = {} & \bar{\psi}(i\gamma_\mu\partial^\mu - \hat{m})\psi \\
& + g_s \sum_{a=0}^{8}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2] \\
& - g_v \sum_{a=0}^{8}[(\bar{\psi}\gamma_\mu\lambda^a\psi)^2 + (\bar{\psi}\gamma_5\gamma_\mu\lambda^a\ \psi)^2] \\
& + g_t\{\det[\bar{\psi}(1+\gamma_5)\psi] + \det[\bar{\psi}(1-\gamma_5)\psi]\},
\end{aligned}
$$

In this work we consider the following set of parameters (Kunihiro 1989; Ruivo et al. 1999): $\Lambda = 631.4$ MeV, $g_s\Lambda^2 = 1.829$, $g_t\Lambda^5 = -9.4$, $m_u = m_d = 5.6$ MeV, $m_s = 135.6$ MeV

Our regime: weak diquark coupling strength.
For calculations in the strong diquark coupling strength regime see Bonanno & Sedrakian A&A 2012.

Thermodynamic potential:

$$\Omega = -\eta N_c \sum_i \int_{k_{Fi}}^{\Lambda} \frac{p^2\,dp}{2\pi^2} \sqrt{p^2 + M_i^2} + 2g_s \sum_i \langle \bar{\psi}\psi \rangle_i^2 - 2g_v \sum_i \langle \psi^\dagger \psi \rangle_i^2 + 4g_t \langle \bar{u}u \rangle \langle \bar{d}d \rangle \langle \bar{s}s \rangle - \eta N_c \sum_i \mu_i \int_0^{k_{Fi}} \frac{p^2\,dp}{2\pi^2} - \Omega_0,$$

Conventional procedure: Fix the Ω_0 term through the condition: $\Omega(T=0,\mu=0) = 0$ (arbitrary way to uniquely determine the EoS without any further assumptions).

in the MIT bag model, for instance, the pressure in the vacuum is non-vanishing.

Other choices lead to significant changes in the EoS: e.g. Pagliara & Schaffner-Bielich (PRD 2008) fix a bag constant for deconfinement to occur at the same chemical potential as the chiral phase transition.

OUR WORK: $\Omega_0 \rightarrow \Omega_0 + \delta\Omega_0$ ($\delta\Omega_0$ is a free parameter)

(*Lenzi & Lugones, ApJ 2012*)

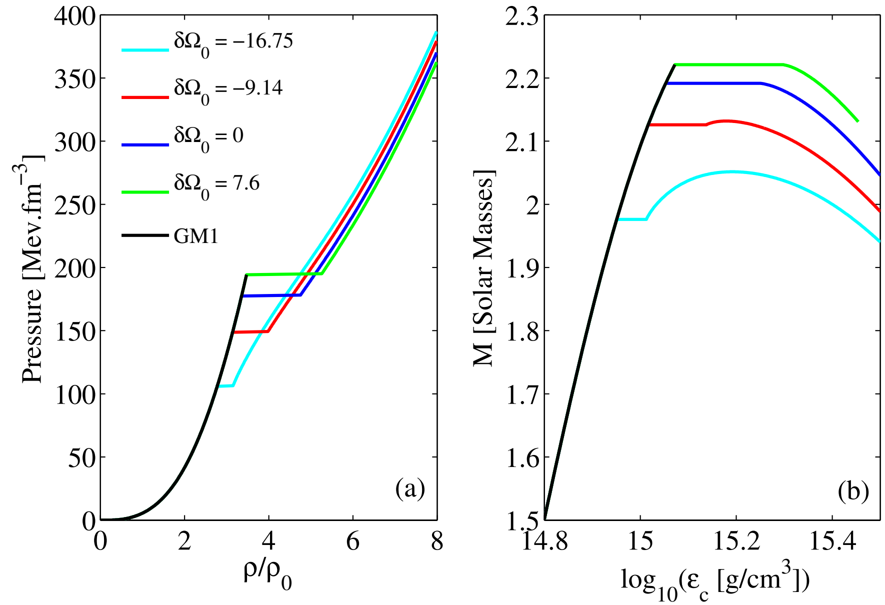
- the μ at which the chiral transition occurs doesn't depend on Ω_0 → it is determined from the solution of the gap equations for the constituent masses.
- the μ for the deconfinement transition depends on Ω_0 because it is determined by matching the pressures of the hadronic and quark phases.
- Thus, tuning $\delta\Omega_0$ is an easy way to control the splitting between both chemical potentials.

Similar to the conjecture of quarkionic matter: the deconfinement and chiral transitions split from one another at the critical point (McLerran & Pisarski 2007) → quarkyonic phase: a confined but chiral symmetric phase, can exist in the region of high μ.

EFFECT OF THE VECTOR COUPLING CONSTANT g_v AND OF $\delta\Omega_0$

Increase $\delta\Omega_0$

- Larger deconfinement pressure
- Smaller quark cores
- Larger maximum masses because the hadronic EoS is stiffer than the quark EoS.
- **Less stable:** there is a larger **density jump** between the two phases, which tends to destabilize the star.



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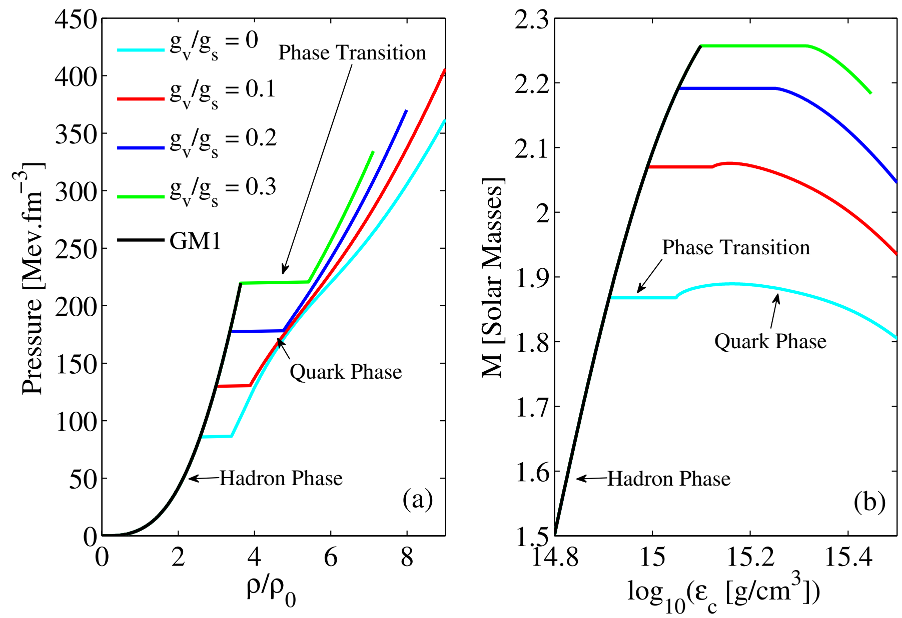
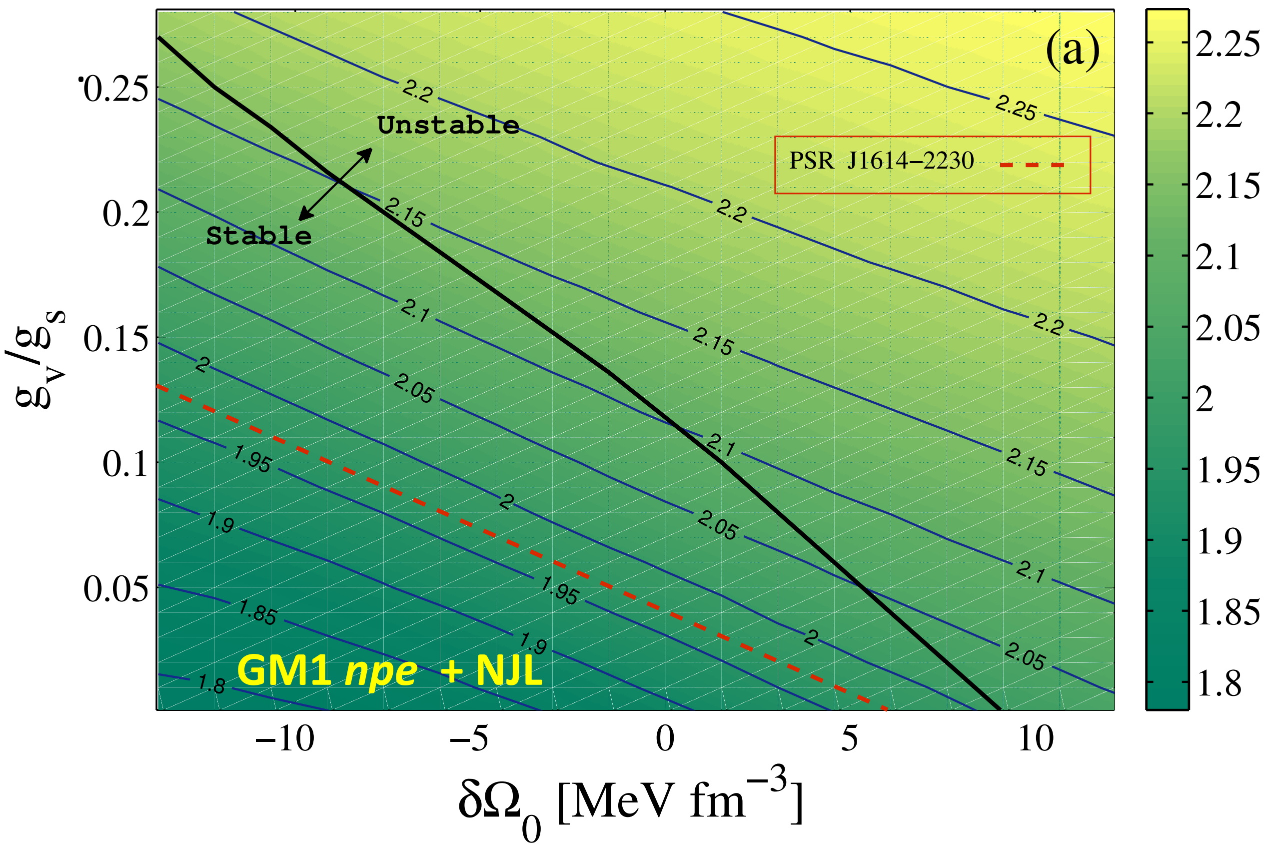
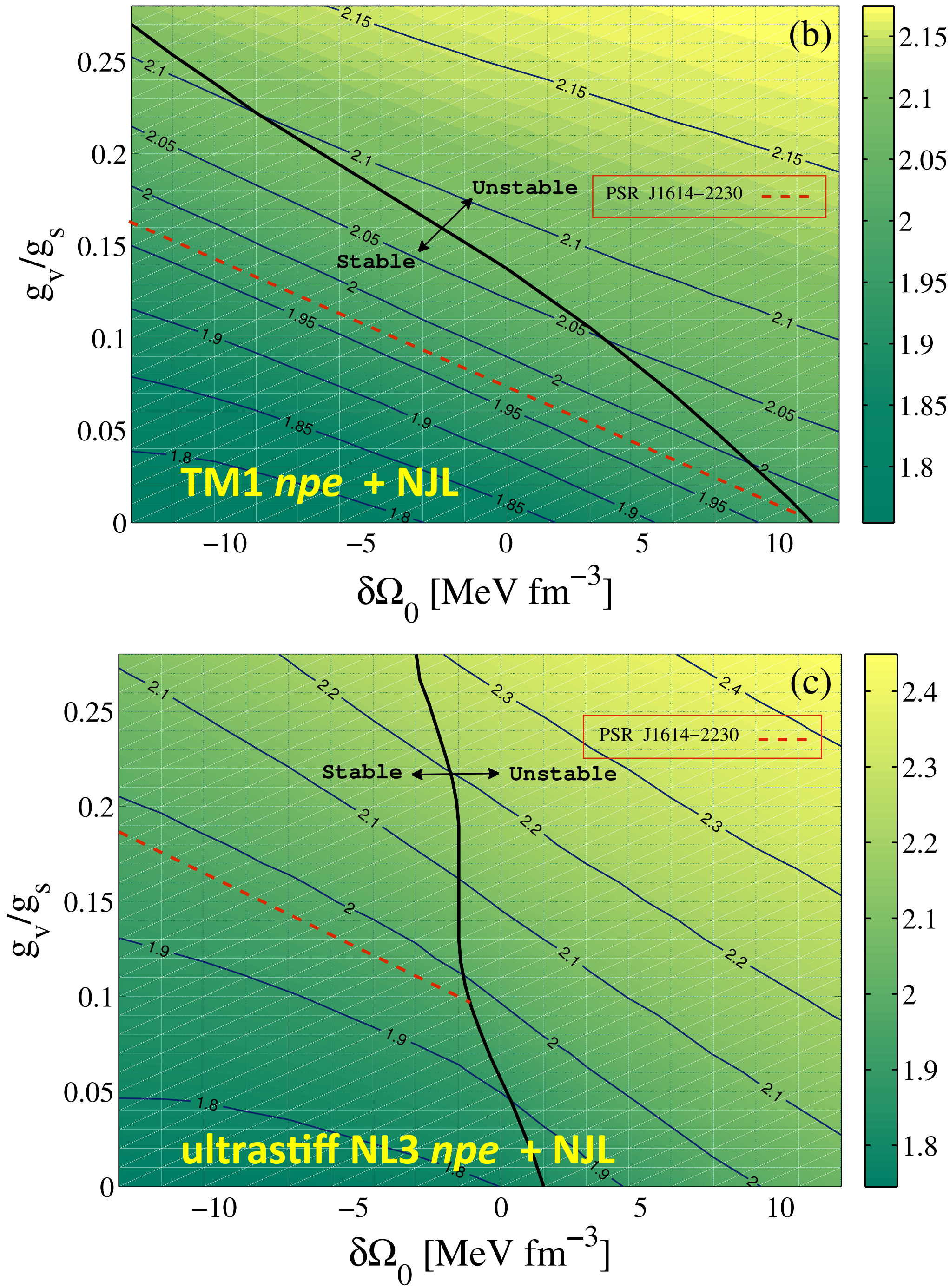




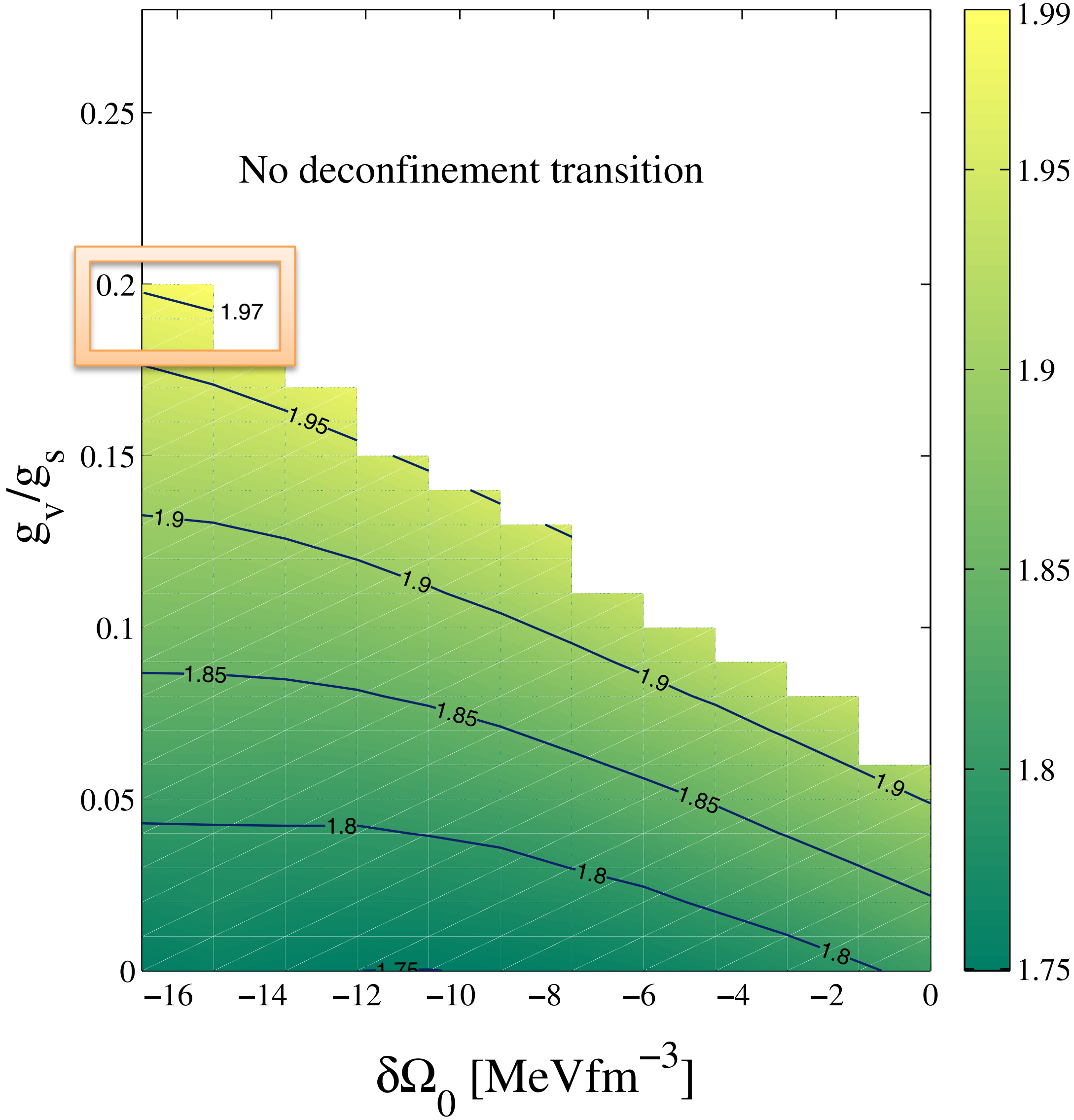
- Background colors and contour lines indicate the maximum mass.
- **black line:** limit between parameters that allow for stable hybrid stars and those that always give unstable hybrid stars.
- **red dashed line:** mass of PSR J1614−2230.

- large masses are situated on the right-upper corner
- stable configurations are located on the left-lower corner
- stable configurations with a maximum mass compatible with PSR J1614−2230 and PSR J0348-0432 are located halfway (between the red and black lines)



EFFECT OF HADRONIC EOS: stable hybrid stars have higher values of the maximum mass for the stiffer hadronic EoS.

Effect of hyperons in the hadronic EoS : NL3 hyp + NJL



For small g_v or $\delta\Omega_0$, the maximum mass values are altered by a few percent (because the deconf. transition occurs at relatively low pressures).

As we increase g_v or $\delta\Omega_0$, the deconfinement transition is shifted to larger pressures and the hadronic EoS with hyperons tends to be favored.
→ Above a certain limit there is no deconfinement transition at all.

CONCLUSIONS 1

- We show that hybrid configurations in agreement with PSR J1614−2230 and PSR J0348-0432 are possible for a significant region of the parameter space of g_v and $\delta\Omega_0$ provided a stiff enough hadronic EoS without hyperons is used.

- The "bag constant" $\delta\Omega_0$ has a strong impact on the structure of neutron stars and deserve more study within other models for the EoS.

2. Discriminating compact stars through GWs of pulsation modes

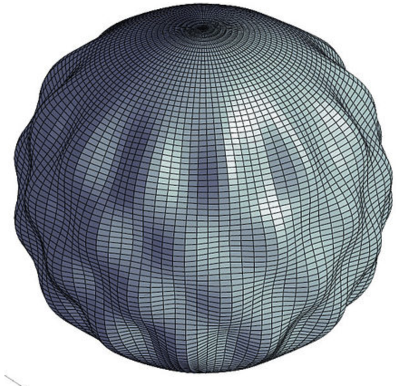
Flores & Lugones; arXiv:1310.0554

→ We investigate non-radial fluid oscillations of hadronic, hybrid and strange quark stars with maximum masses above the mass of PSR J1614-2230 and PSR J0348-0432.

MOTIVATION

1. Advanced LIGO and Advanced VIRGO will bring within the next few years the science of gravitational radiation to a mode of regular astrophysical observation

2. Non-radial oscillations are sources of gravitational radiation. The pulsation modes depend on the EOS.



EQUATIONS OF STATE

- ***Hadronic matter:*** RMFM with neutrons, protons and electrons → GM1 & NL3 parametrizations.

- ***Quark matter:*** MIT bag model.

$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B,$$

QCD interactions are roughly incorporated through the parameter a_4 (e.g. Alford et al. 2005, Weissenborn et al. 2011).

$$\Omega_{\rm CFL} = \Omega_{\rm free} - \frac{3}{\pi^2}\Delta^2\mu^2 + B,$$

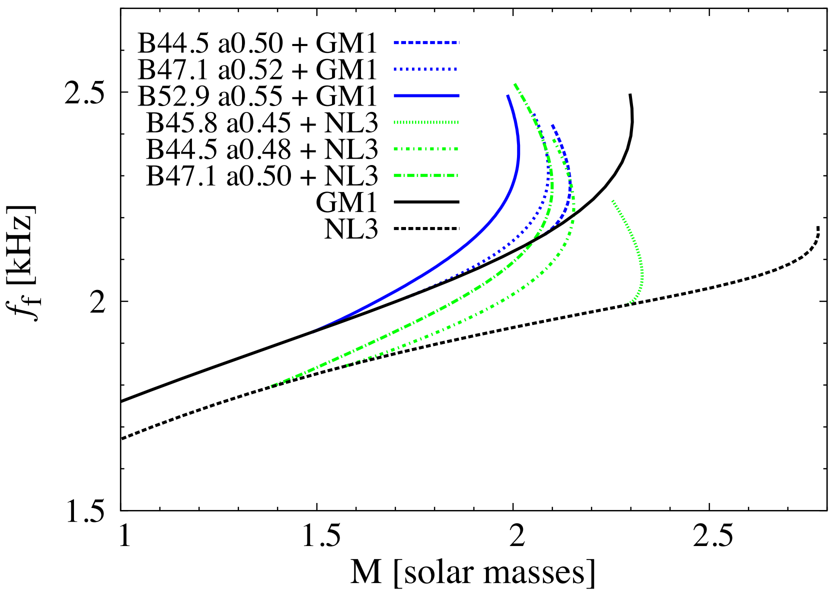
Effect of color superconductivity: CFL strange matter (e.g. Lugones & Horvath 2002)

PULSATION EQUATIONS

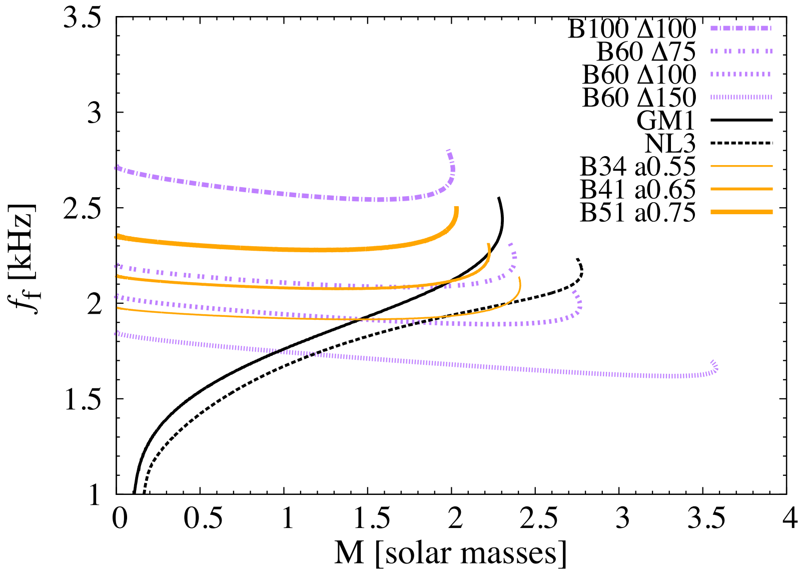
The relativistic equations of non-radial oscillations were integrated within the Cowling approximation.
Errors of Cowling approx. with respect to full linearized calculation: less than 20 % for f mode, less than 10 % for p_1 and less than few % for g-modes (Sotani et al. 2011).

Fundamental mode

Hadronic & Hybrid Stars



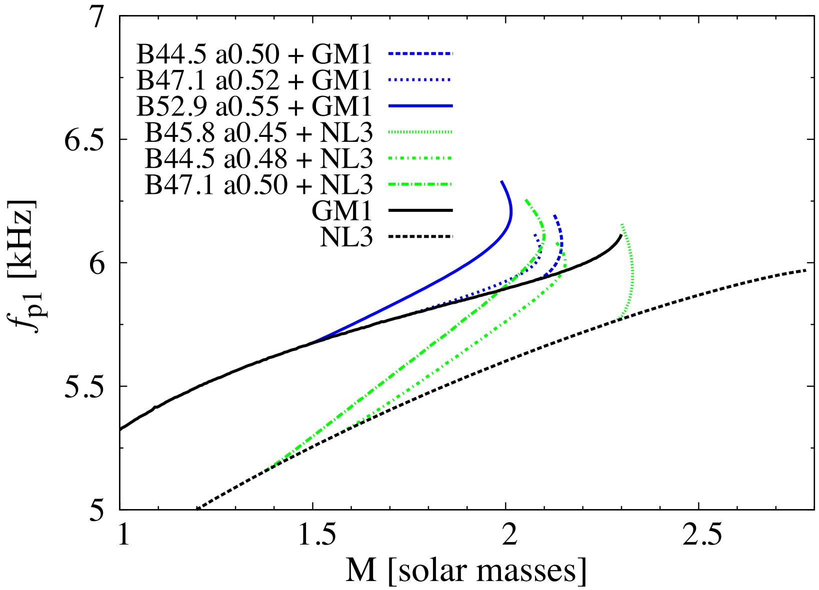
Hadronic & Strange Stars



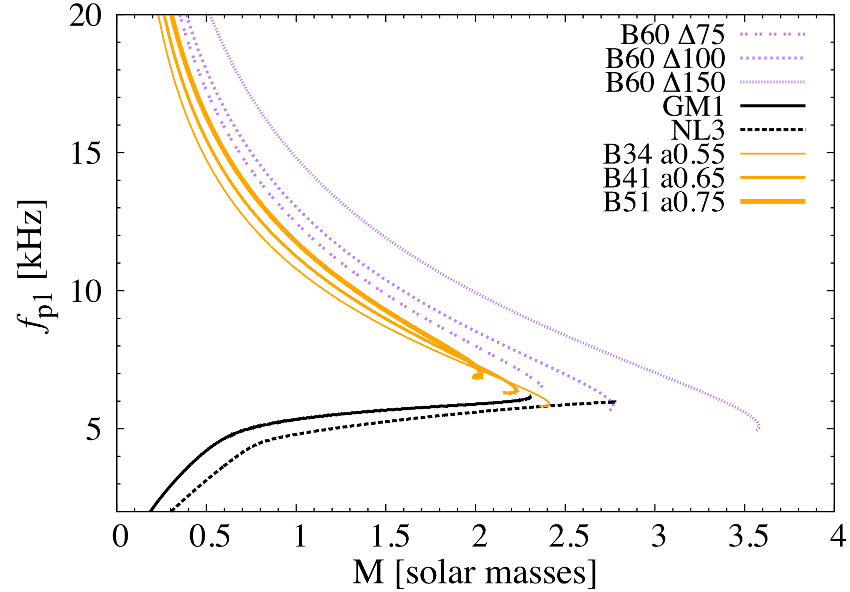
- there is an overlapping of the curves corresponding to hadronic, hybrid and strange quark stars for stellar masses larger that ~ 1 $M_\odot$
- difficult to distinguish hybrid and hadronic stars even if the mass or the surface z of the object is determined together with f_f
- However, in some cases we can discriminate strange stars and hadronic/hybrid stars.
  - strange stars cannot emit GWs with frequency below ~ 1.7 kHz
  - sources with M = 1-1.5 $M_\odot$ emitting a signal in the range 2-3 kHz would be strange stars.

First pressure mode

Hadronic & Hybrid Stars



Hadronic & Strange Stars



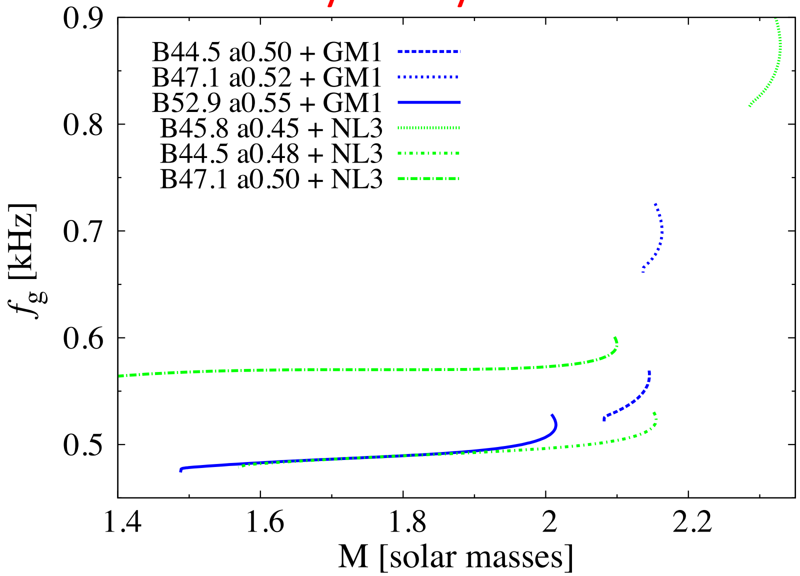
f_{p1} is much more affected by the internal composition of the star:

- for hadronic and hybrid stars, we find that fp1 is in the range 4 – 6 kHz for objects with masses in the range 1 – 2 $M_\odot$
- for strange quark stars it is always significantly larger than ~ 6 kHz.

Thus, a compact object emitting a signal above ~ 6 kHz could be identified as a strange star even if its mass or gravitational redshift are unknown.

g-mode due to the hadron-quark discontinuity

Only for Hybrid Stars



- High frequency g-modes are only present in hybrid stars and fall in the range 0.4 – 1 kHz.

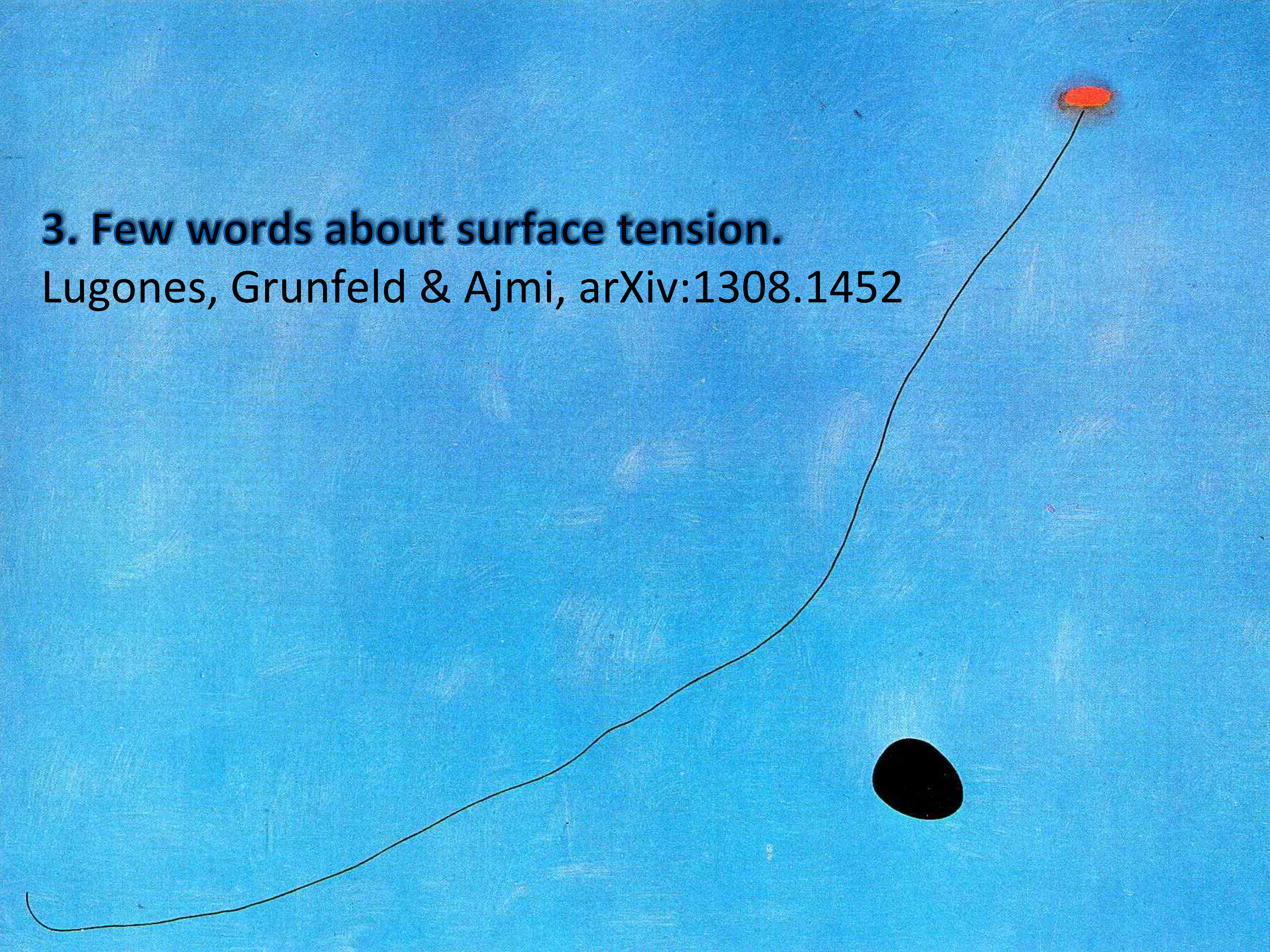
- Clearly distinguishable from:
  - the fundamental mode,
  - low-frequency g-modes associated with chemical inhomogeneities in the outer layers or thermal profiles (Miniutti, Pons, Berti, Gualtieri, Ferrari 2003).

CONCLUSIONS 2

	f_f	f_{p1}	f_g
strange stars	~ 2 kHz	> 6 kHz	not present
hybrid stars	~ 2 kHz	$\sim 4 - 6$ kHz	$\sim 0.4 - 1$ kHz
hadronic stars	~ 2 kHz	$\sim 4 - 6$ kHz	not present

- compact objects emitting a signal above 6 kHz should be interpreted as strange quark stars (p1 mode is large)

- compact objects emitting a signal in the range ~ 0.4–1 kHz should be interpreted as hybrid stars (hadron-quark discontinuity g mode)



3. Few words about surface tension.

Lugones, Grunfeld & Ajmi, arXiv:1308.1452

Surface Tension: a wide range, 5–300 MeV/fm^2:

1. Lima, Avancini & Providência (2013) 0.5-1 MeV/fm^2
2. Early calculations (Berger & Jaffe 1987) values below 5 MeV/fm^2
3. Palhares & Fraga (2010): 5–15 MeV/fm^2
4. Pinto, Koch & Randrup (2012): NJL within a geometrical approach 5 − 30 MeV/fm^2
5. Voskresensky, Yasuhira & Tatsumi (2003) 50 − 150 MeV/fm^2
6. Lugones, Gunfeld & Ajmi (2013) 150-160 MeV/fm^2, NJL with MRE.
7. Alford, Rajagopal, Reddy & Wilczek: ~ 300 MeV/fm^2, on the basis of dimensional analysis of the minimal interface between a color-flavor locked phase and nuclear matter.

OUR CALCULATION: $SU(3)_f$ NJL effective model which also includes color superconducting quark-quark interactions

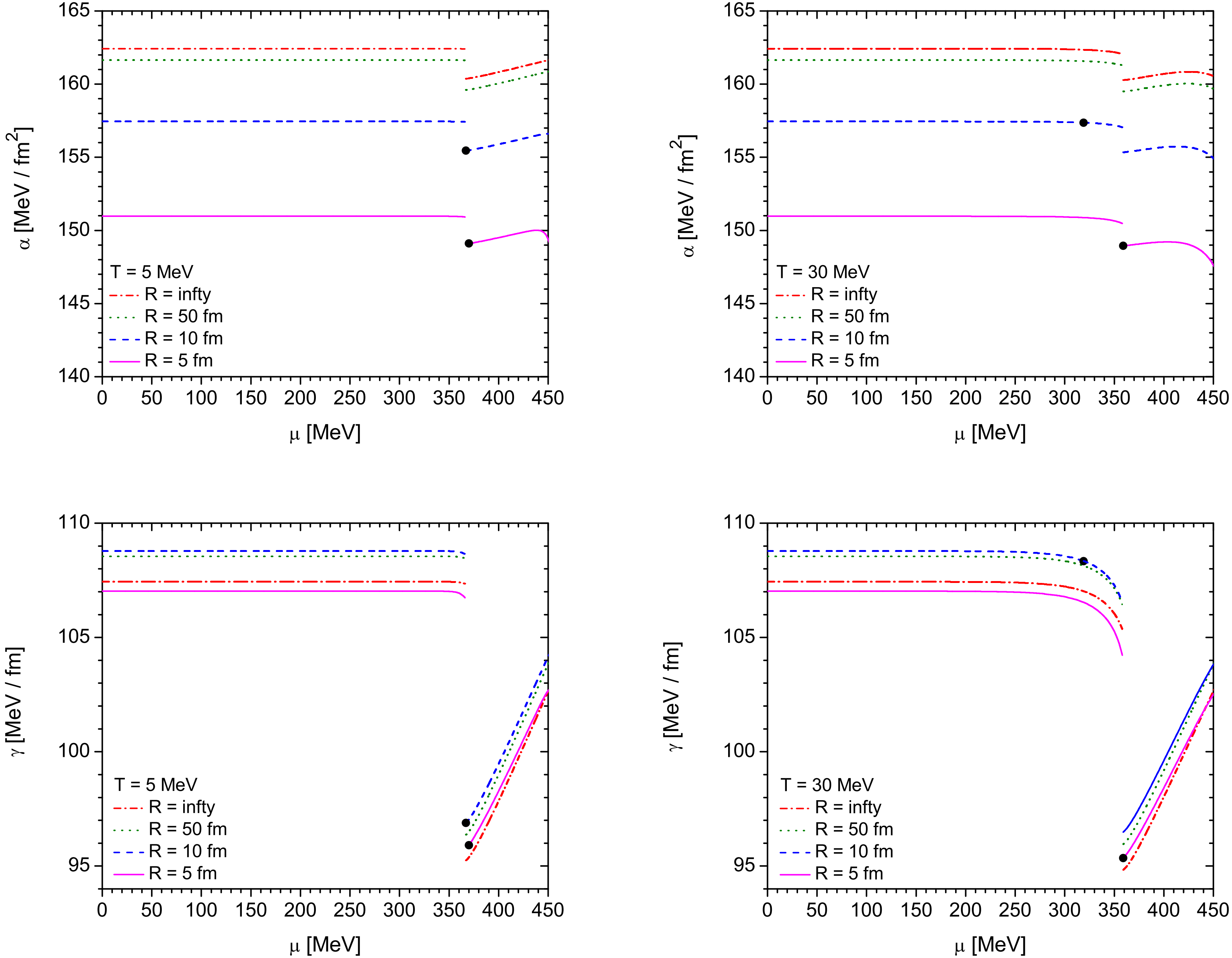
$$
\begin{aligned}
\mathcal{L} \; = & \; \bar{\psi}\left(i\partial\!\!\!/ - \hat{m}\right)\psi \\
& + \; G\sum_{a=0}^{8}\left[\left(\bar{\psi}\;\tau_a\;\psi\right)^2 + \left(\bar{\psi}\;i\gamma_5\tau_a\;\psi\right)^2\right] \\
& + \; 2H\sum_{A,A'=2,5,7}\left[\left(\bar{\psi}\;i\gamma_5\tau_A\lambda_{A'}\;\psi_C\right)\left(\bar{\psi}_C\;i\gamma_5\tau_A\lambda_{A'}\;\psi\right)\right]
\end{aligned}
$$

Multiple Reflection Expansion Formalism (MRE), Balian & Bloch (1970), Madsen (1994), Kiriyama & Hosaka (2003), Kiriyama (2005).

$$
\int_0^{\Lambda}\cdots\frac{k^2\,dk}{2\pi^2} \longrightarrow \int_{\Lambda_{IR}}^{\Lambda}\cdots\frac{k^2\,dk}{2\pi^2}\rho_{MRE}.
$$

Density of states for the case of a finite spherical droplet

$$
\rho_{MRE}(k, m_f, R) = 1 + \frac{6\pi^2}{kR}f_S + \frac{12\pi^2}{(kR)^2}f_C
$$



165
160
155
150
145
140
α [MeV / fm²]
0 50 100 150 200 250 300 350 400 450
μ [MeV]
T = 5 MeV
R = infty
R = 50 fm
R = 10 fm
R = 5 fm
T = 30 MeV
R = infty
R = 50 fm
R = 10 fm
R = 5 fm
110
105
100
95
γ [MeV / fm]
T = 5 MeV
R = infty
R = 50 fm
R = 10 fm
R = 5 fm
T = 30 MeV
R = infty
R = 50 fm
R = 10 fm
R = 5 fm

Thank you !

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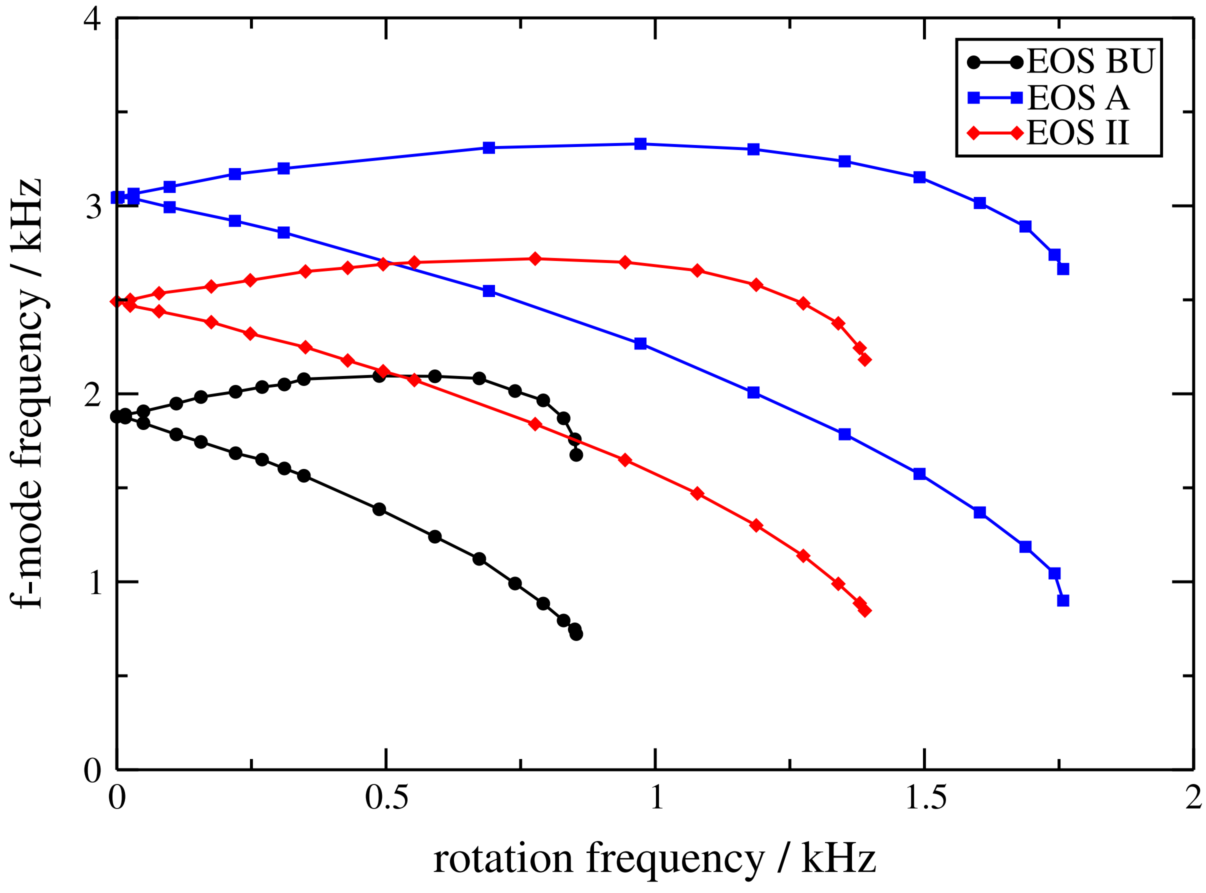
Effect of rotation: Gaertig & Kokkotas PRD 2009



- $\delta\Omega_0$ has a minimum value because the deconfinement transition cannot be shifted to a pressure regime where the NJL model describes the vacuum.

- That is, we fix a minimum limit to $\delta\Omega_0$ for which the phase transition occurs at the chiral symmetry restoration point as performed by Pagliara & Schaffner-Bielich (2008).

- On the other hand, in principle there is no maximum value for $\delta\Omega_0$ since the phase transition can be shifted to arbitrarily large pressures.