Hadron-quark phase transition in hybrid stars and first insights for generating a new supernova EOS

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Overview

Quark matter in SN and NS

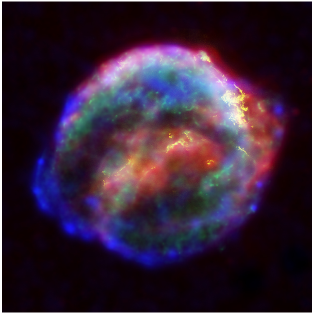

Figure : Type IIb Supernova SN 1993J

Source: `http://imgsrc.hubblesite.org/hu/db/images/hs-2004-29-b-full_jpg.jpg`

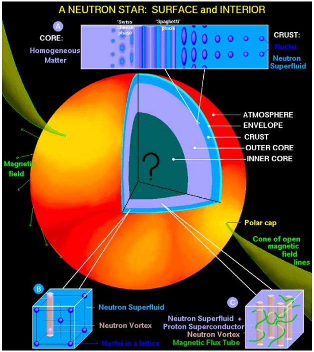

Figure : Cross-section NS

Source: Dany Page,
`http://inspirehep.net/record/1266411/plots`

Hadron-Quark Phase Transition in NS

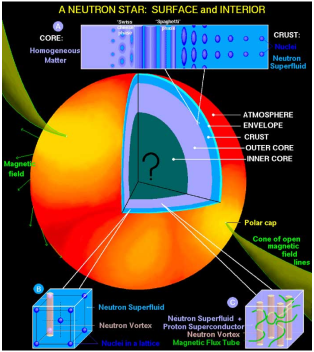

Figure : Cross-section NS

Source: Dany Page,
`http://inspirehep.net/record/1266411/plots`

Observations

- 2 precise measurements of 2 $M_\odot$ neutron stars.
- Demorest pulsar: PSR J1614-2230, (1.97 ± 0.04) $M_\odot$.
- Antoniadis pulsar: PSR J0348+0432, (2.01 ± 0.04) $M_\odot$.

- Quark matter (QM) plausible due to high densities in the core of NS.
- Pure quark stars possible (Witten 1984), as well as hybrid stars.
- Inset of QM leads to softening of EOS $\rightarrow$ lowering of maximum mass.
- 2 $M_\odot$ NS are possible (Benic 2014, Weissenborn 2011, Alford 2005, 2013, Blaschke 2015)

Hadron-Quark Phase Transition in SN

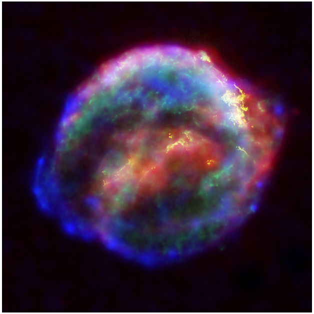

Figure : Type IIb Supernova SN 1993J

Source: `http://imgsrc.hubblesite.org/hu/db/images/hs-2004-29-b-full_jpg.jpg`

- Working mechanism shown by Sagert et al. (2009)
- Second collapse $\rightarrow$ second shockwave $\rightarrow$ triggers delayed SN explosion
- 2nd shockwave visible in ν signal
- Works in 1D
- Promising due to high explosion energies and self-consistent mechanism.

Problem

Until now, only shown with EOS that do not support 2 $M_\odot$ NS.

SN to NS

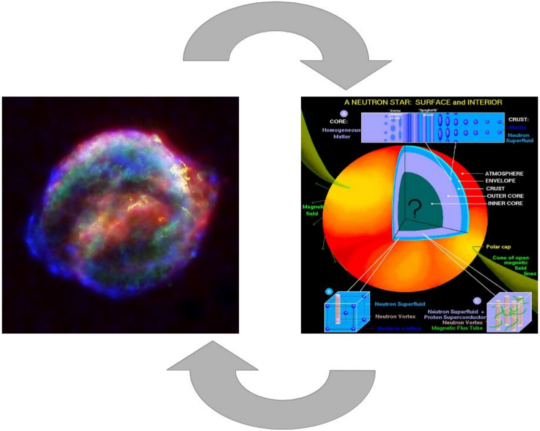

Figure : SN and NS

Key Questions

- Which kind of hybrid stars are still possible? $\rightarrow$ Classification
- Which quark models are compatible?
- Which parameter configuration might be promising for a new SN EOS?

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Hybrid Star Model

Definition

Hybrid stars are neutron stars that consist of both, hadronic and quark matter.

Overview of the model used:

- Scenario introduced by Alford et al. (2013)
- Hadronic phase: HS(DD2) (new)
- Quark phase: Constant Speed of Sound approach (CSS) with density independent speed of sound (Alford 2013)
- Phase transition: Maxwell construction (Alford 2013)

Hadronic EOS: HS(DD2)

- Supernova EOS table at finite temperature and variable proton fraction available
  (Hempel & Schaffner-Bielich 2010, Fischer et al. 2014).
- Density-dependent relativistic mean field theory
  (DD2, Typel et al. 2010)
- Matter consists of n, p, e, A
- Nuclear matter properties are in good agreement with many different nuclear experiments.
- Maximum mass: 2.42 $M_\odot$

Important

HS(DD2) EOS describes neutron star from crust to the outer core self-consistently. In this work: HS(DD2) at $T = 0.1$ MeV and β-equilibrium.

Quark EOS

In this work: Generic quark EOS proposed by Alford et al.

Constant Speed of Sound EOS

$$\epsilon_{QM}(p) = c_{QM}^{-2}(p - p_{trans})$$

Properties:

- density-independent speed of sound c_{QM}
- $c_{QM}^2 = 1/3$ corresponds to weakly interacting massless quarks.
- $c_{QM}^2 = 1$ corresponds to strongly interacting quarks. Maximal value to be still consistent with SRT.

Isn't it too simple?

CSS shows good agreement for case $c_{QM}^2 = 1/3$ to more sophisticated models, as e.g. Nambu-Jona-Lasinio (NJL) (e.g. Benić 2014), Field-Correlator-Method (FCM) (Zappala 2014), pertubative quark matter EOS (pQCD) (Kurkela et al. 2010).

The Hybrid EOS

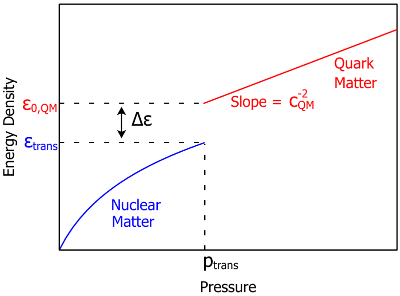


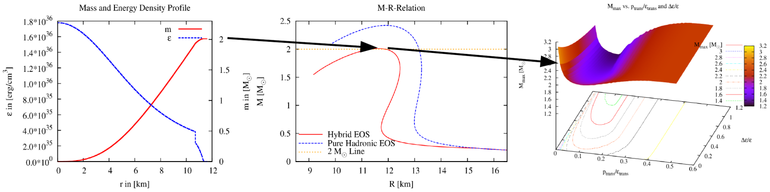
Figure : Schematic representation of the hybrid star EOS used Source: Alford, 2013

Maxwell Construction

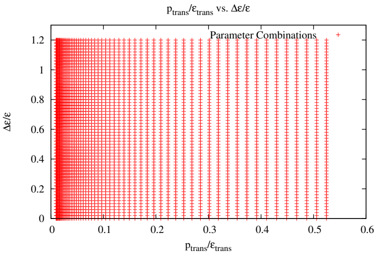
1st order phase transition with a density jump at constant pressure from hadron to quark matter, based on local charge neutrality.

$$\epsilon(p) = \begin{cases} \epsilon_{HS(DD2)}(p) & p < p_{trans} \\ \epsilon_{HS(DD2)}(p_{trans}) + \Delta\epsilon + c_{QM}^{-2}(p - p_{trans}) & p > p_{trans} \end{cases}$$

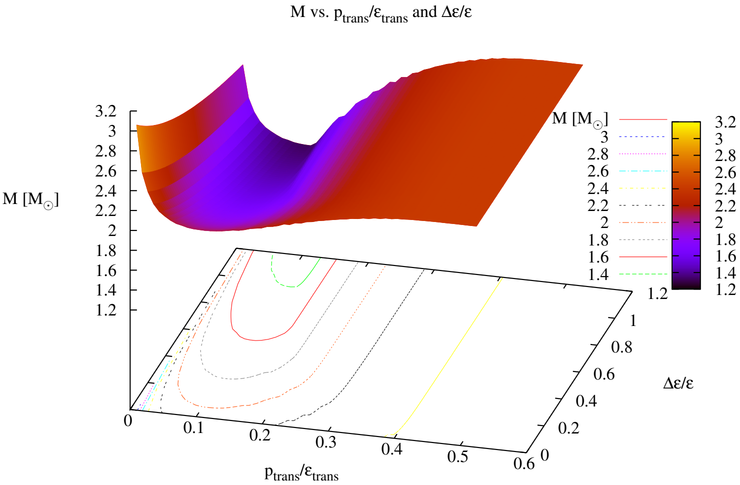
Sequence of Calculations



- Determination of M-R relation by solving TOV equations.
- Variation of input parameters p_{trans}, $\Delta\epsilon$.
- 60 x 60 parameter combinations
- $p_{trans\_min} = 1 \cdot 10^{-4}$ MeV/fm^3 ($n_B \sim 0.10$ fm^{-3})
- $p_{trans\_max} \approx 700$ MeV/fm^3 ($n_B \sim 0.96$ fm^{-3})
- $c^2_{QM\_0} = 1/3$
- $\Delta\epsilon/\epsilon = [0, 1.2]$

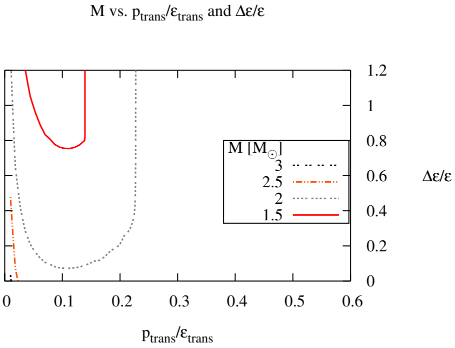


Results: Mass-Distribution



Mass-Distribution: Contour Lines

- Masses over maximum mass of HS(DD2) ($M_{max} = 2.42\ M_\odot$)
- Stars with high maximum masses are almost pure quark stars.



Alford's Classification of Hybrid Stars

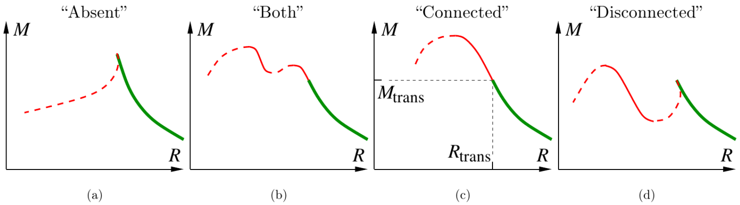
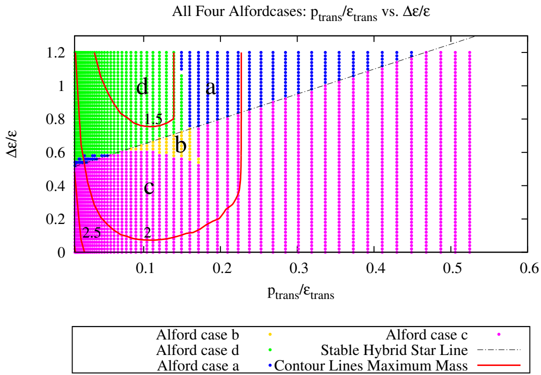
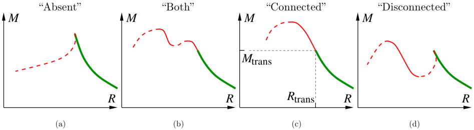


Figure : Four different possible M-R relation curves Source: Alford, 2013

- Two criteria for distinction:
  Third family and continuous hybrid branch
- Third family: Hadronic phase building up → set in phase transition → phase of instability → new stable branch
- Case b) and d): 2 staged collapse → interesting for SN

Results: Alfords Cases and Mass Contour Lines





Stable Hybrid Star Line

Analytic criterion derived by Seidov 1971

$$\frac{\Delta\epsilon_{crit}}{\epsilon_{trans}} = \frac{1}{2} + \frac{3}{2}\frac{p_{trans}}{\epsilon_{trans}}$$

Comparison of Quark Models

- CSS is not a common parameterization for quark models!
- Often bag model is used.
- Question: How do these models compare to the CSS model used before?

Interacting model of Alford respectively Weissenborn 2005

Idea: Introduce phenomenological interaction term a_4 (and possibly a_2).

Alford (Weissenborn) model

$$\Omega_{\mathrm{QM}} = \underbrace{\underbrace{\sum_{i=u,d,s,e} \Omega_i - \frac{3\mu^4}{4\pi^2}(1-a_4) + B_{\mathrm{eff}}}_{\text{Weissenborn et al. (2011)}} + \left(\frac{3\mu^2}{4\pi^2} a_2\right)}_{\text{Alford et al. (2005)}}$$

- a_4 term accounts for strong interaction QCD corrections
- a_2 can be interpreted as a term to take color superconductivity into account. In this case: $a_2 = m_s^2 - 4\Delta^2$ (Δ pairing gap).
- Here: Parameters are treated as generic interaction terms, which are freely varied without respect to their physical meaning.

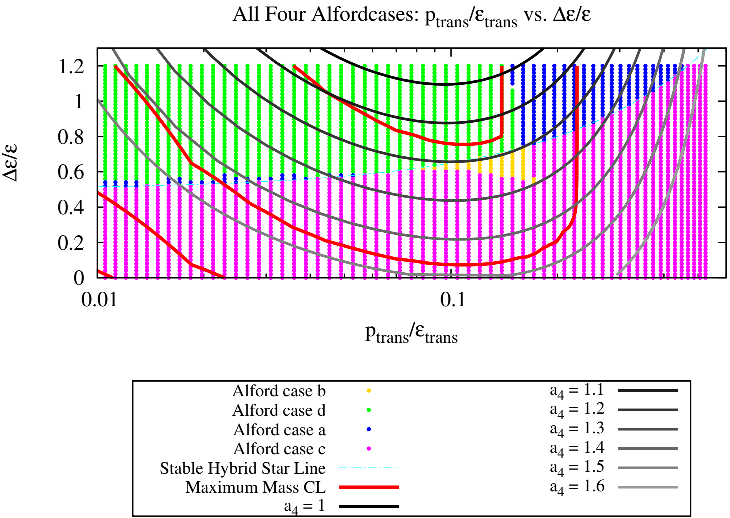
Direct identification of Weissenborn's BAG model with CSS EOS

- Assumptions: $m_s = 0$ and $c_s^2 = 1/3$, $a_2 = 0$, non-vanishing a_4 term.

$$a_4 = 2 - \frac{\pi^2}{3}\frac{\epsilon_0 + P_0}{\mu_0^4}$$

$$B_{\mathrm{eff}} = \frac{1}{4}\epsilon_0 - \frac{3}{4}P_0$$

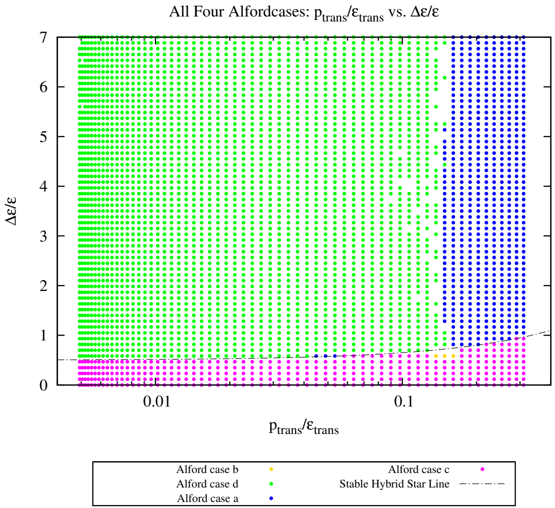
Interacting model with fixed a_4-term, $m_s = 0$, $c_s^2 = 1/3$ and varying $B^{1/4}$



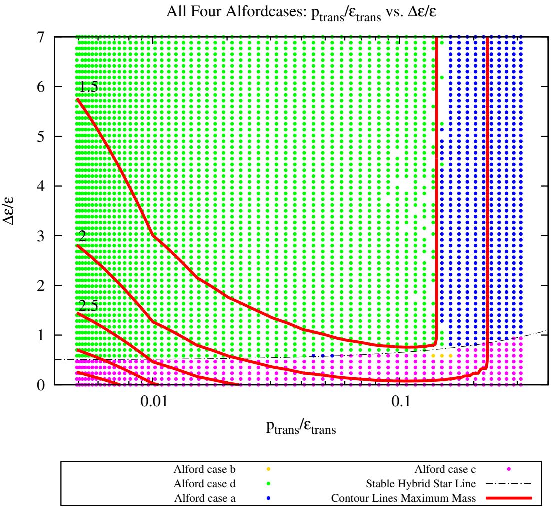
Existing hadron-quark SN EOS

$B^{1/4} = 162$ MeV	Sagert et al. 2009	1.56 $M_\odot$	explosion
$B^{1/4} = 165$ MeV	Sagert et al. 2009	1.50 $M_\odot$	explosion
$B^{1/4} = 155$ MeV, $a_s = 0.3$	Sagert et al. 2011	1.67 $M_\odot$	explosion
$B^{1/4} = 139$ MeV, $a_s = 0.7$	Sagert et al. 2011	2.04 $M_\odot$	
$B^{1/4} = 145$ MeV, $a_s = 0.7$	Sagert et al. 2011	1.97 $M_\odot$	

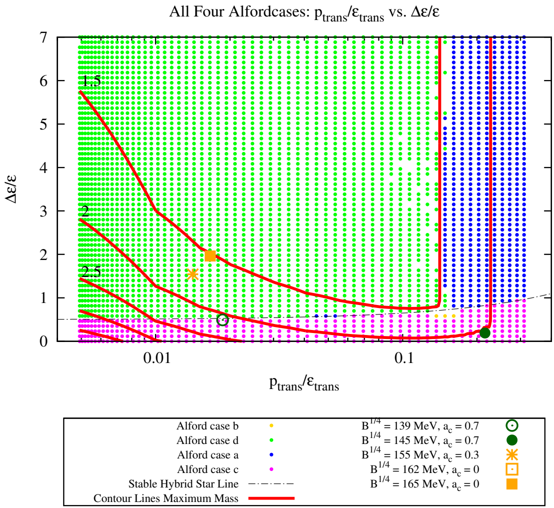
Restricting the parameter space



Restricting the parameter space



Restricting the parameter space



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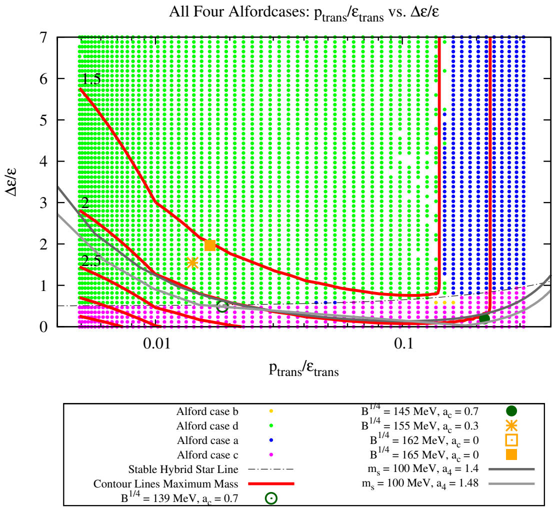
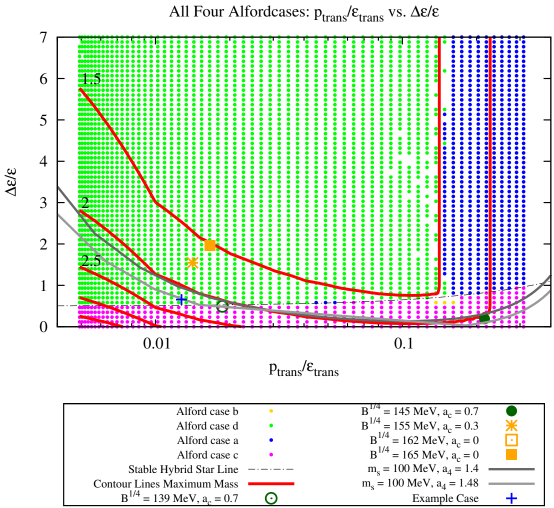
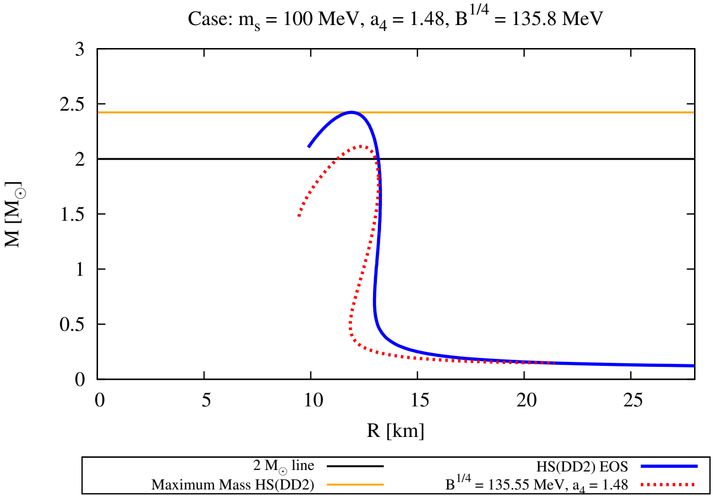


Restricting the parameter space



Example


Case: m_s = 100 MeV, a_4 = 1.48, B^1/4 = 135.8 MeV
M [M_☉]
R [km]
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
2 M_☉ line
Maximum Mass HS(DD2)
HS(DD2) EOS
B^1/4 = 135.55 MeV, a_4 = 1.48

Summary

What have we (hopefully) learned today?

- Hybrid stars with third family branches and masses over 2 $M_\odot$ are found.
- Very high mass stars are almost pure quark stars.
- 1:1 correspondence between Constant Speed of Sound model and bag model exists.
- Parameter space for hybrid SN EOS candidates is very restricted.
- A promising candidate with $m_s = 100$ MeV, $a_4 = 1.48$ and $B^{1/4} = 135.8$ MeV is presented.

Thank you for your attention