Exotic convection inside hybrid stars

A. Yudin

ITEP, Moscow

In collaboration with M. Hempel, D. Nadyozhin and T. Razinkova

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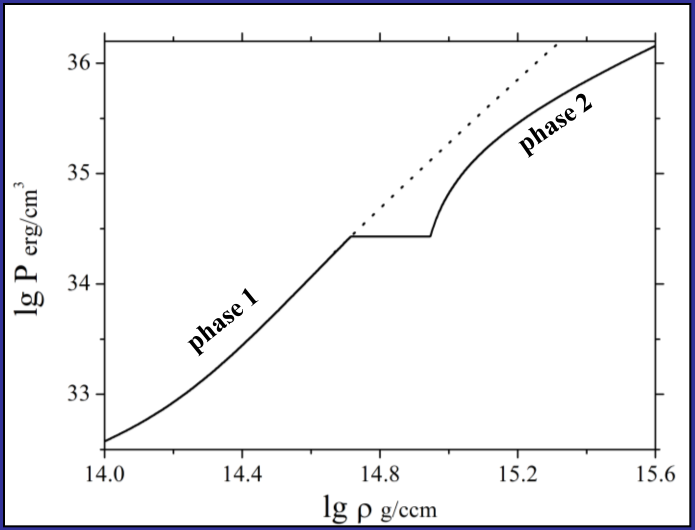
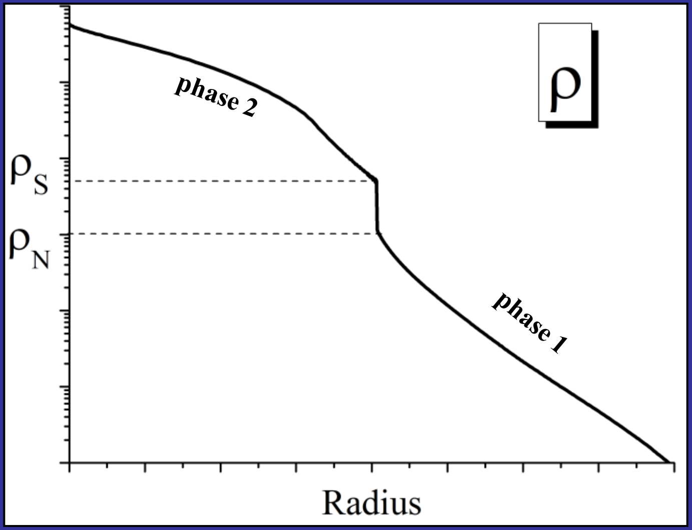
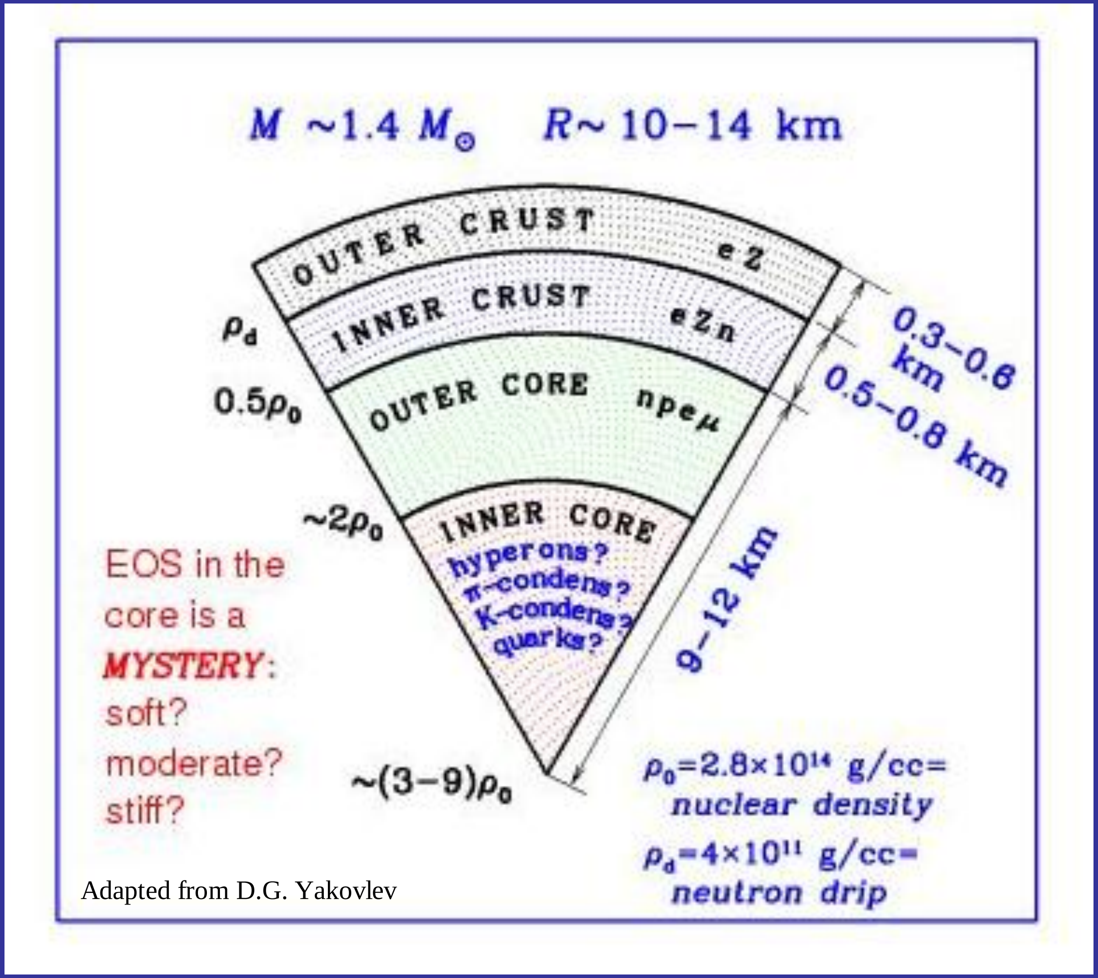
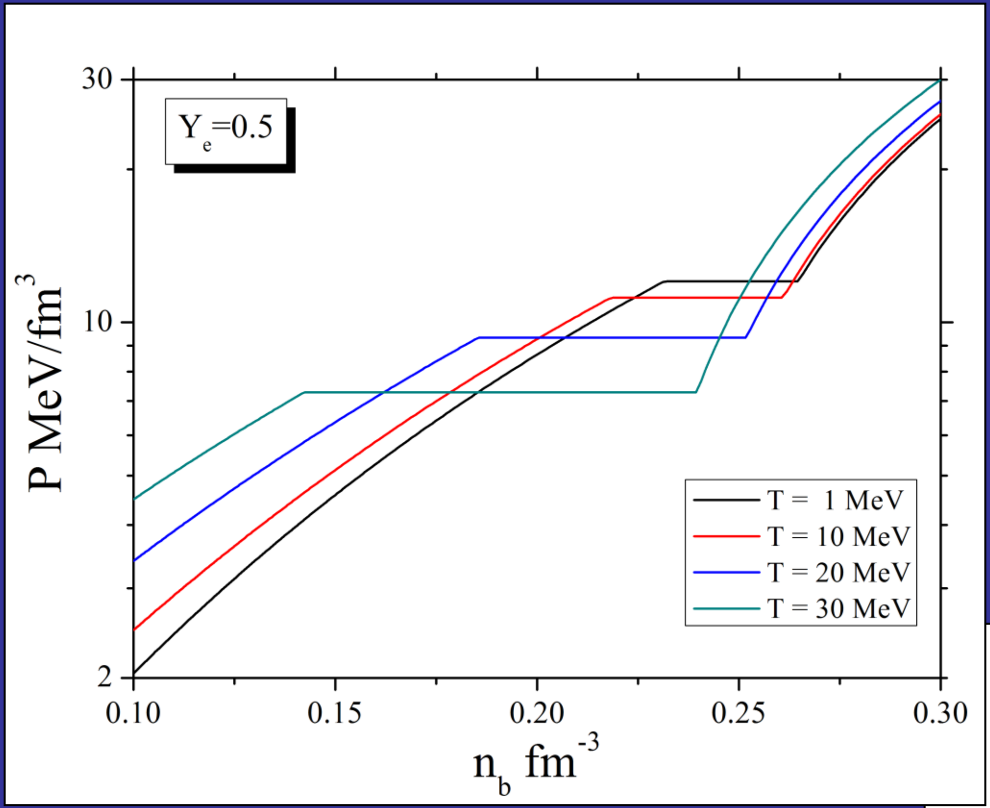
Neutron/hybrid star





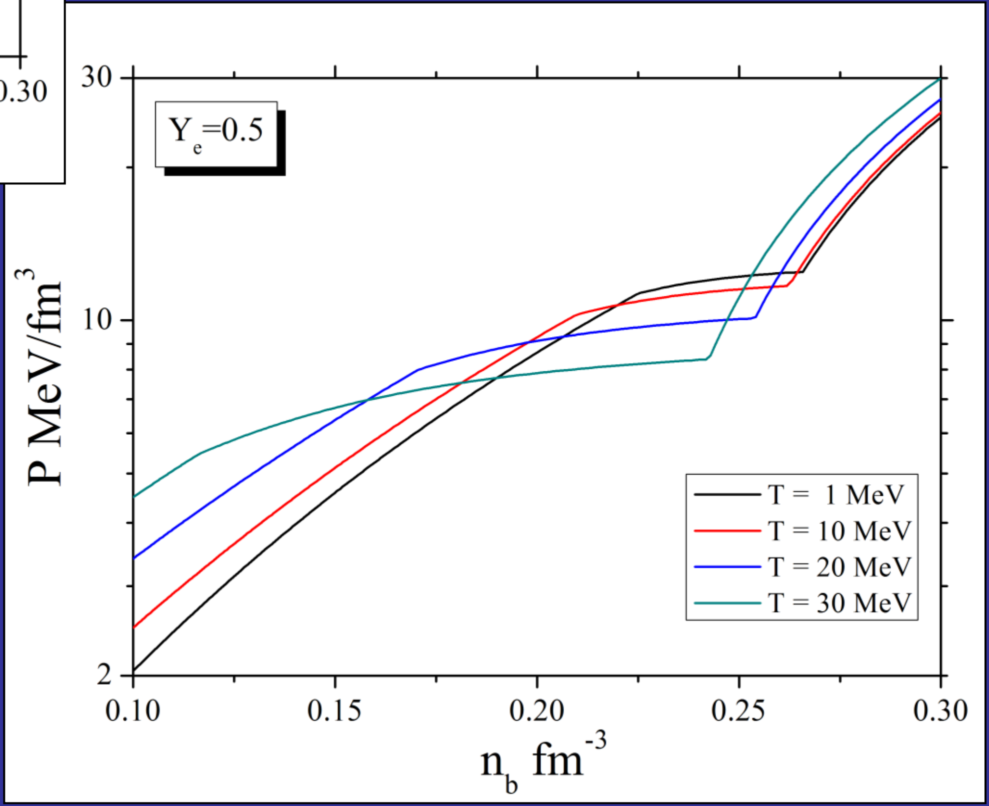
Maxwellian type phase transition causes a density jump inside the star





Maxwell Phase Transition

Gibbs Phase Transition



Global or local charge neutrality
N.K. Glendenning (1992)

$$P_I(n_n, n_p, n_e^I, T) = P_{II}(n_{up}, n_{dw}, n_s, n_e^{II}, T)$$

$$\mu_n = \mu_{up} + 2\mu_{dw}$$

$$\mu_p = 2\mu_{up} + \mu_{dw}$$

$$\mu_e^I = \mu_e^{II}$$

$$\mu_s = \mu_{dw}$$

Mixing phase: the most interesting place inside the star

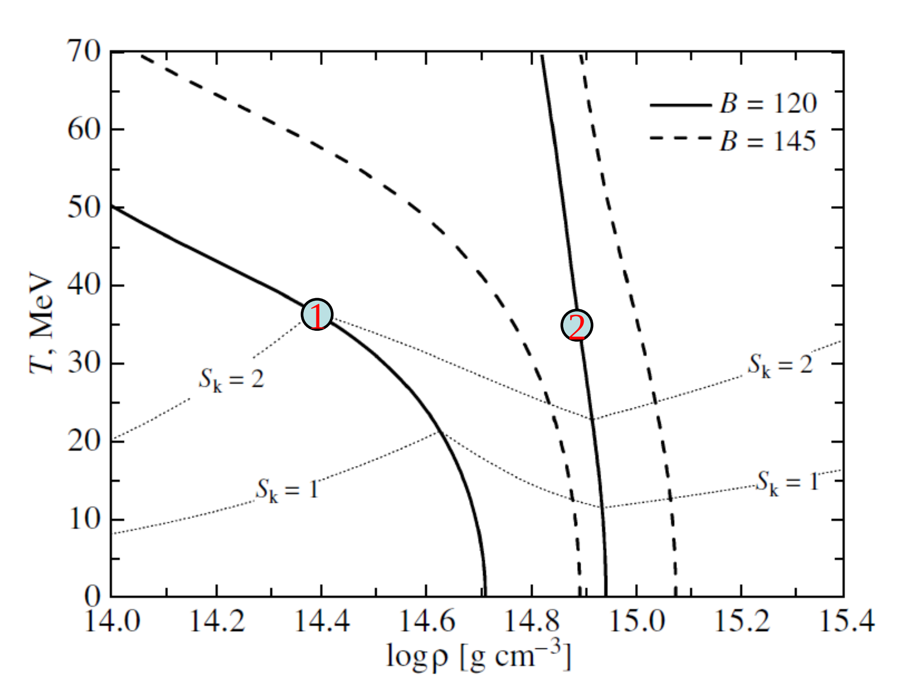
Clapeyron–Clausius

$$\left(\frac{\partial P}{\partial T}\right)_{\rm pt} = \frac{S_1 - S_2}{\frac{1}{\rho_1} - \frac{1}{\rho_2}} < 0,$$

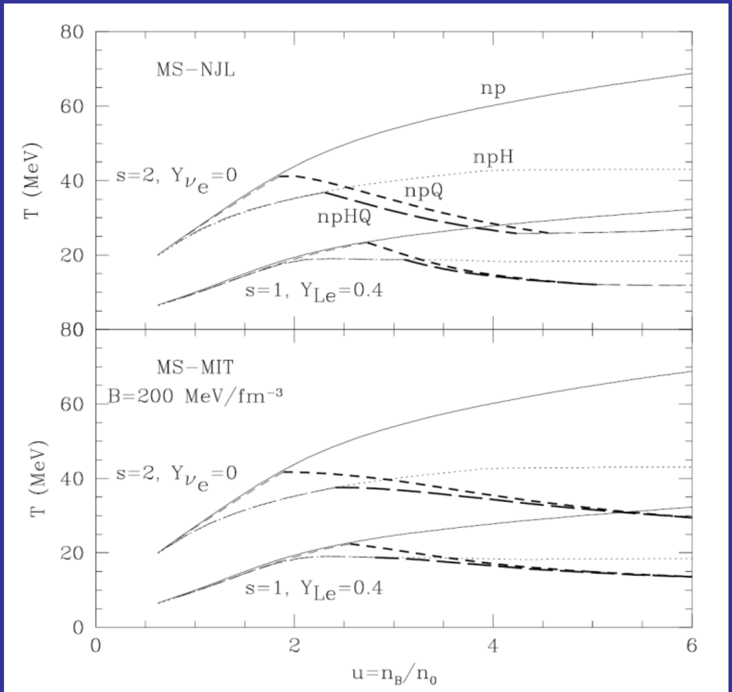
$$\triangle q = T(S_2 - S_1) > 0.$$

Noncongruence of the nuclear liquid-gas and deconfinement phase transitions

M. Hempel, V. Dexheimer, S. Schramm, and I. Iosilevskiy
Phys. Rev. C 88, (2013)



Quark-Hadron Phase Transitions in Young and Old Neutron Stars
A. Steiner, M. Prakash, and J.M. Lattimer
Physics Letters B, Volume 486, Issue 3-4, p. 239-248.



Convective instability condition

$$\begin{cases} \triangle\epsilon_{\rm ce} = \left(\frac{\partial\epsilon}{\partial P}\right)_{S,Y} \triangle P, \\ \triangle\epsilon_{\rm sm} = \left(\frac{\partial\epsilon}{\partial P}\right)_{S,Y} \triangle P + \left(\frac{\partial\epsilon}{\partial S}\right)_{P,Y} \triangle S + \left(\frac{\partial\epsilon}{\partial Y}\right)_{P,S} \triangle Y, \end{cases}$$

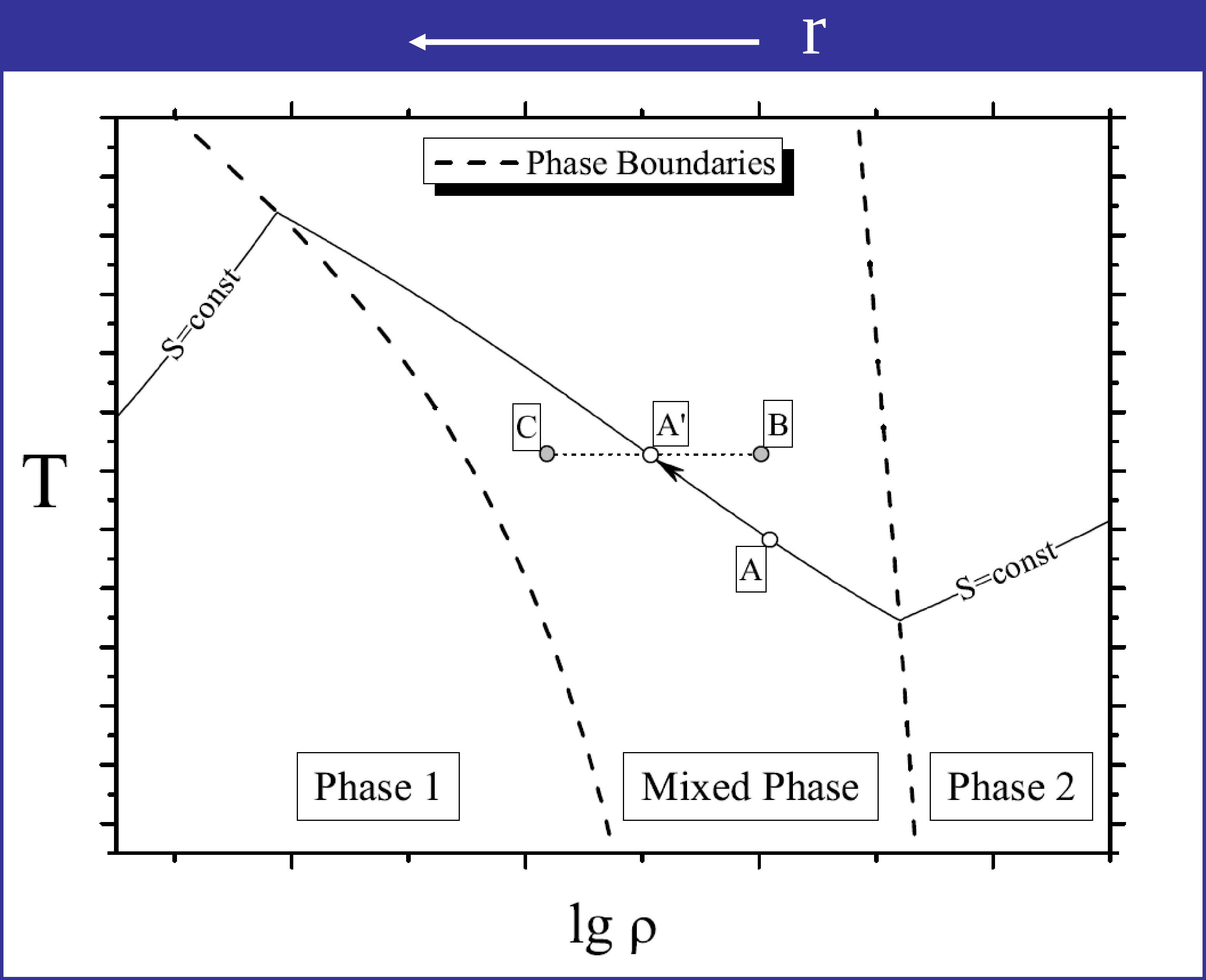
Energy (density) change inside convective element and surrounding matter

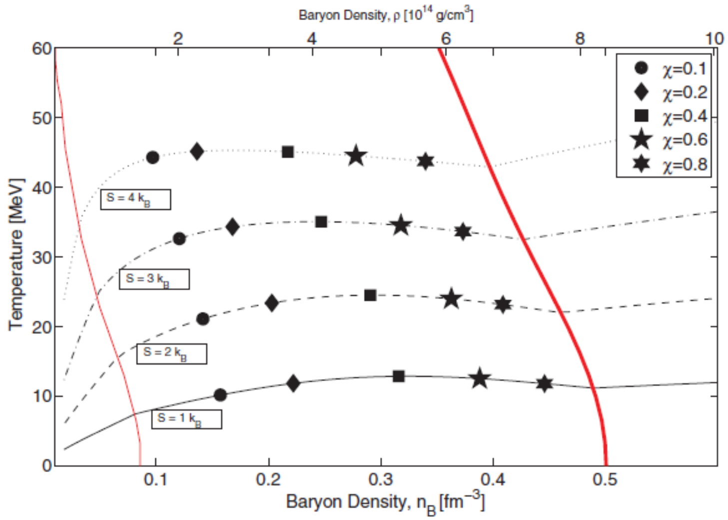
$$\left(\frac{\partial\epsilon}{\partial S}\right)_{P,Y} \frac{dS}{dr} + \left(\frac{\partial\epsilon}{\partial Y}\right)_{P,S} \frac{dY}{dr} > 0.$$

$$\left(\frac{\partial\rho}{\partial S}\right)_{P} = -\frac{\rho^2}{\left(\frac{\partial P}{\partial T}\right)_S} = -\frac{T\rho}{P\gamma c_{\rm V}} \left(\frac{\partial P}{\partial T}\right)_{\rho}$$

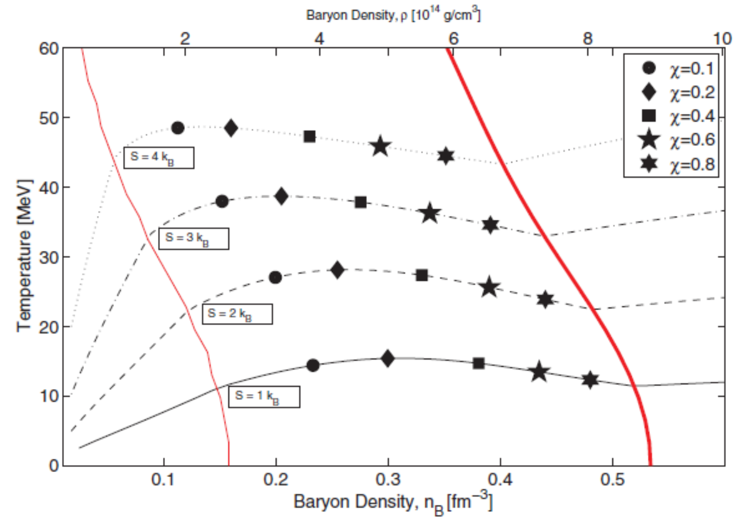
$$\left(\frac{\partial\epsilon}{\partial S}\right)_{P,Y} = \rho T \left[1 - \frac{\epsilon + P}{T\left(\frac{\partial P}{\partial T}\right)_S}\right]$$

Schematic explanation

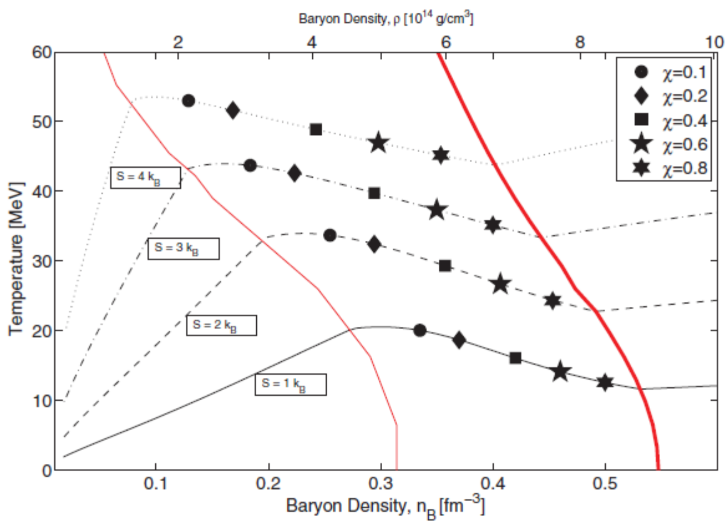




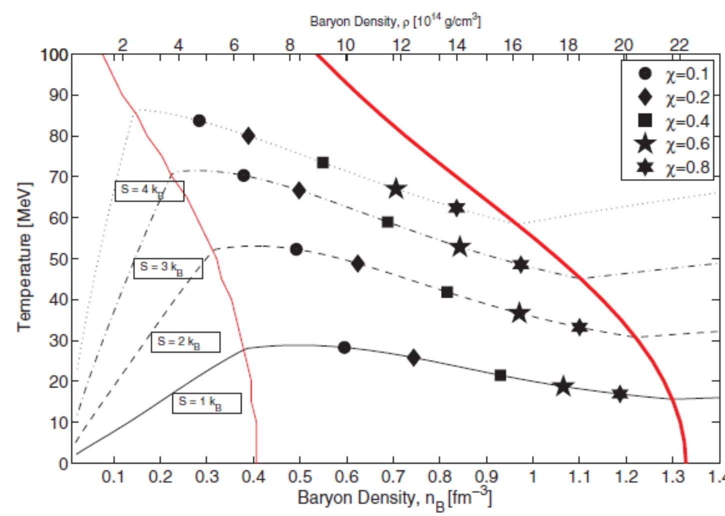
(a) $Y_p = 0.1$ ($B^{1/4} = 165$ MeV, $\alpha_S = 0$)



(b) $Y_p = 0.3$ ($B^{1/4} = 165$ MeV, $\alpha_S = 0$)



(c) $Y_p = 0.5$ ($B^{1/4} = 165$ MeV, $\alpha_S = 0$)



(d) $Y_p = 0.3$ ($B^{1/4} = 200$ MeV, $\alpha_S = 0$)

Figure 6. Temperature evolution in the mixed phase for the different entropies per baryon $s = 1, 2, 3, 4\ k_B$. Graphs (a)–(c) show calculations for global proton fractions of $Y_p = 0.1$, $Y_p = 0.3$, and $Y_p = 0.5$ with $B^{1/4} = 165$ MeV. The red solid lines show the onset of the mixed phase (thin lines) and the beginning of the pure quark phase (thick lines) and are the same as in Figure 5(a). For comparison, graph (d) shows the temperature evolution in the mixed phase for $Y_p = 0.3$ and $B^{1/4} = 200$ MeV.

MNRAS **455,** 4325–4328 (2016) doi:1

Some properties of convection in hybrid stars

A. V. Yudin,[1,2]★ M. Hempel,[3]★ D. K. Nadyozhin[1,4]★ and T. L. Razinkova[1]

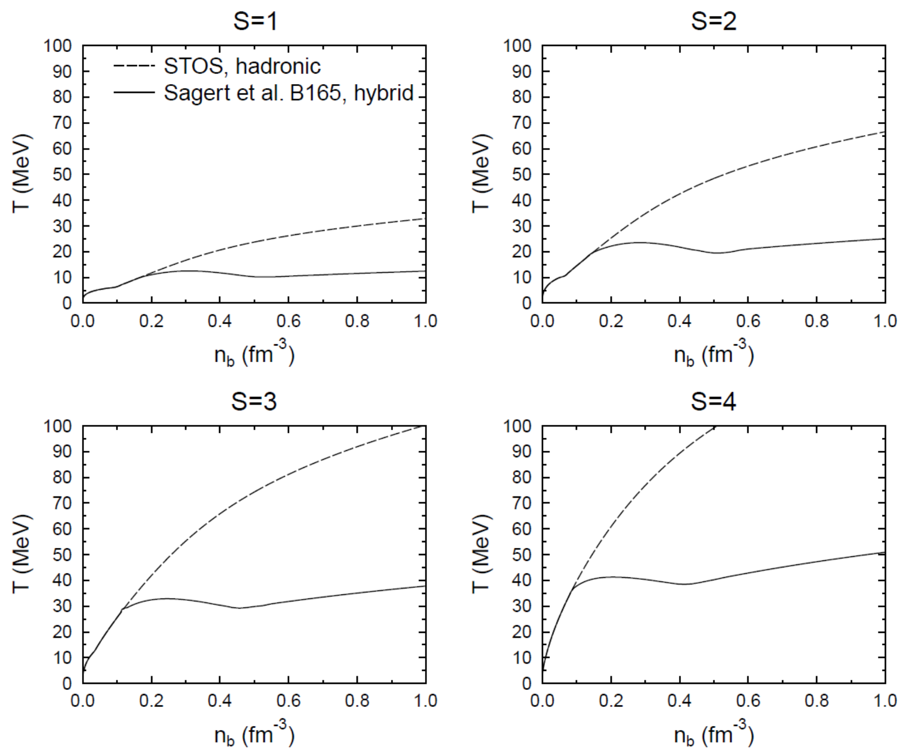


Figure 2. The temperature versus baryon density n_b for hadronic (Shen et al. 2011) and hybrid equations of state (Sagert et al. 2009) (dashed and solid curves, respectively) for various different values of the entropy per baryon S and a fixed lepton fraction of $Y_L = 0.4$.

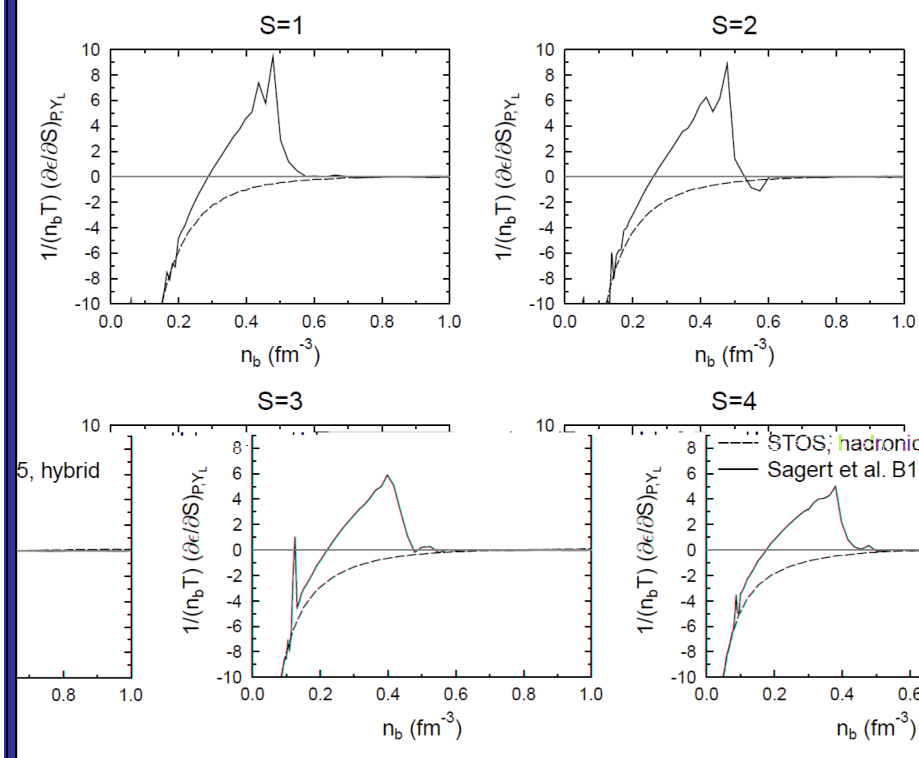


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Figure 3. Derivative $\left(\frac{\partial \varepsilon}{\partial S}\right)_{P,Y}$ multiplied by $\frac{1}{n_b T}$ versus ba sity n_b for hadronic (Shen et al. 2011) and hybrid equ state (Sagert et al. 2009) (dashed and solid curves, resp for various different values of the entropy per baryon S a lepton fraction of $Y_L = 0.4$.

Entropic and enthalpic phase transitions in high energy density nuclear matter

Igor Iosilevskiy[1,2]

[1] *Joint Institute for High Temperatures (Russian Academy of Sciences), Izhorskaya Str. 13/2, 125412 Moscow, Russia*

[2] *Moscow Institute of Physics and Technology (State Research University), Dolgoprudny, 141700, Moscow Region, Russia*

1 Abstract

Features of Gas-Liquid (GL) and Quark-Hadron (QH) phase transitions (PT) in dense nuclear matter are under discussion in comparison with their terrestrial counterparts, e.g. so-called "plasma" PT in shock-compressed hydrogen, nitrogen etc. Both, GLPT and QHPT, when being represented in widely accepted temperature – baryonic chemical potential plane, are often considered as similar, i.e. amenable to one-to-one mapping by simple scaling. It is argued that this impression is illusive and that GLPT and QHPT belong to different classes: GLPT is typical enthalpic PT (Van-der-Waals-like) while QHPT ("deconfinement-driven") is typical entropic PT. Subdivision of 1st-order fluid-fluid phase transitions into enthalpic and entropic subclasses was proposed in [arXiv:1403.8053]. Properties of enthalpic and entropic PTs differ significantly. Entropic PT is always internal part of more general and extended thermodynamic anomaly – domains with abnormal (negative) sign for the set of (usually positive) second derivatives of thermodynamic potential, e.g. Gruneizen and thermal expansion and thermal pressure coefficients etc. Negative sign of these derivatives lead to violation of standard behavior and relative order for many iso-lines in P–V plane, e.g. isotherms, isentropes, shock adiabats etc. Entropic PTs have more complicated topology of stable and metastable areas within its two-phase region in comparison with conventional enthalpic PTs. In particular, new additional metastable region, bounded by new additional spinodal, appears in the case of entropic PT. All the features of entropic PTs and accompanying abnormal thermodynamics region have transparent geometrical interpretation – multi-layered structure of thermodynamic surfaces for temperature, entropy and internal energy as a pressure–volume functions, e.g. $T(P,V)$, $S(P,V)$ and $U(P,V)$.

https://arxiv.org/abs/1504.05850

$$\Delta H = T\Delta S > 0 \Rightarrow \left(\frac{dP}{dT}\right)_{binodal} > 0 \qquad \text{(enthalpic PT)},$$

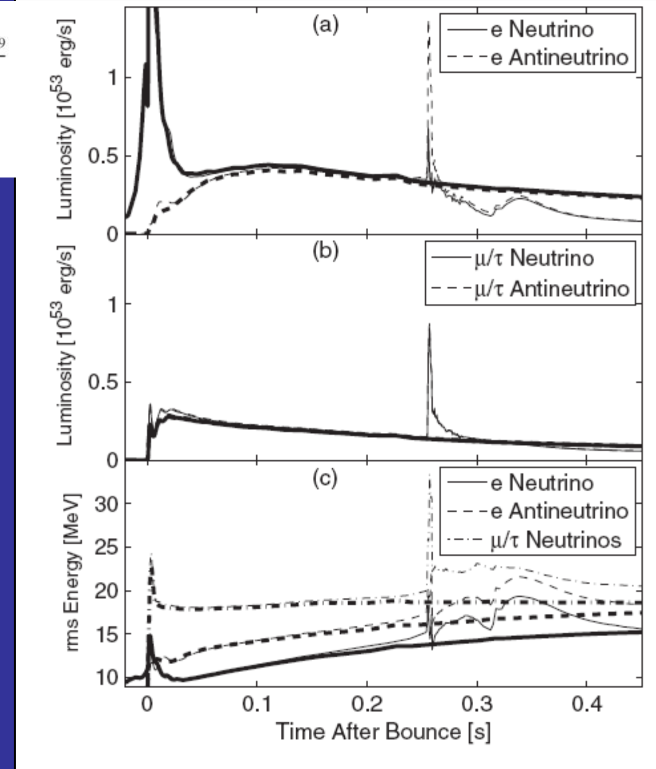
$$\Delta H = T\Delta S < 0 \Rightarrow \left(\frac{dP}{dT}\right)_{binodal} < 0 \qquad \text{(entropic PT)}.$$

$$\begin{array}{ccccc}
(\partial P/\partial T)_V & \leftrightarrow & (\partial P/\partial S)_V & \leftrightarrow & (\partial P/\partial U)_V \\
\updownarrow & & \updownarrow & & \updownarrow \\
(\partial V/\partial T)_P & \leftrightarrow & (\partial V/\partial S)_P & \leftrightarrow & (\partial V/\partial H)_P \\
\updownarrow & & & \updownarrow & \\
(\partial S/\partial V)_T & \leftrightarrow & & (-\partial S/\partial P)_T & \\
\updownarrow & & & \updownarrow & \\
(\partial T/\partial P)_S & \leftrightarrow & & (-\partial T/\partial V)_S &
\end{array}$$

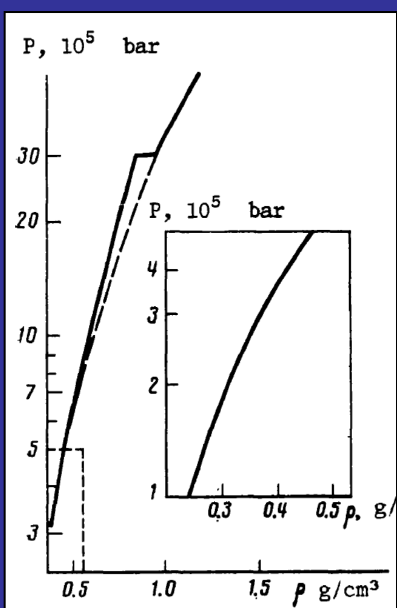

PRL 102, 081101 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

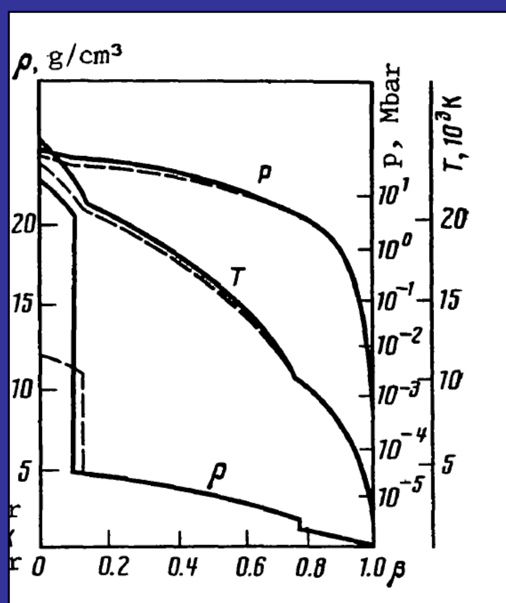
Signals of the QCD Phase Transition in Core-Collapse Supernovae

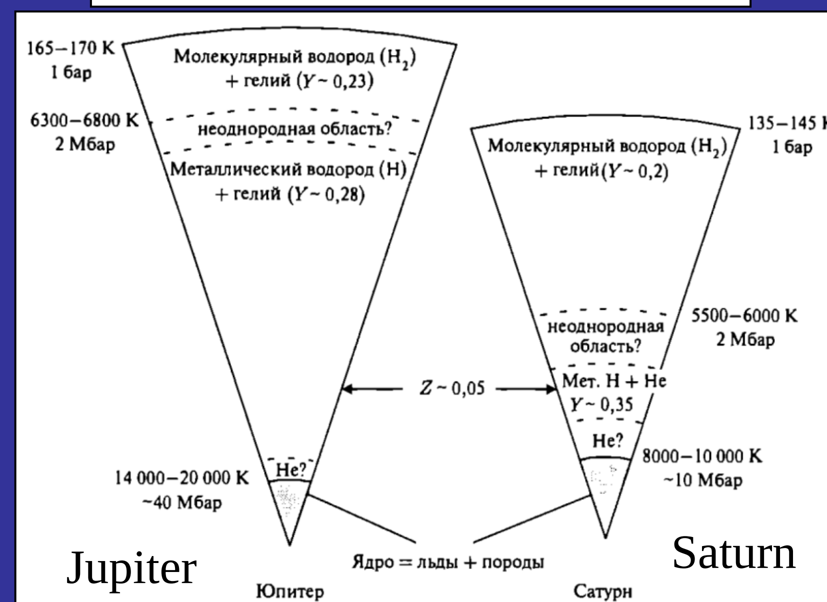
I. Sagert,[1] T. Fischer,[3] M. Hempel,[1] G. Pagliara,[2] J. Schaffner-Bielich,[2] A. Mezzacappa,[4] F.-K. Thielemann,[3] and M. Liebendörfer[3]



- Supernova explosion
- NS cooling
- Giant planets







T.V. Gudkova, V.N. Zharkov and V.V. Leontev
Soviet Astronomy Letters, Vol.14, NO. 2/MAR, P. 157, 1988

From "Systems of Jupiter and Saturn" by Kuskov, Dorofeeva, Kronrod and Makalkin URSS 2009 (in Russian)

Thank you!