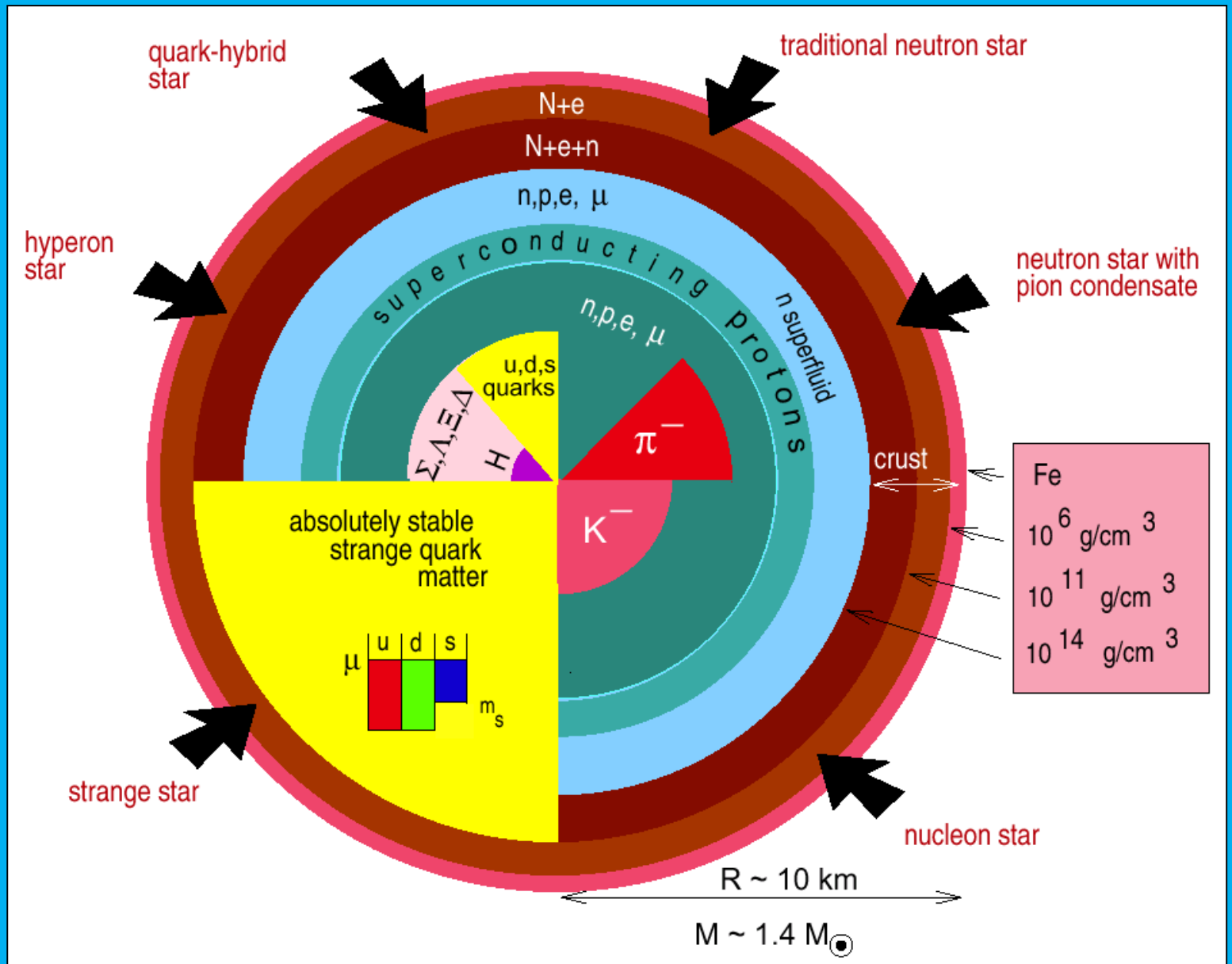
On the possible consequences of multiple phase transitions inside hybrid stars

A. Yudin, T. Razinkova, D. Nadyozhin

The International Conference
SN 1987A, Quark Phase Transition in Compact Objects and Multimessenger Astronomy

2-8 July 2017

Composition of Neutron Star



Ordinary Phase Transition

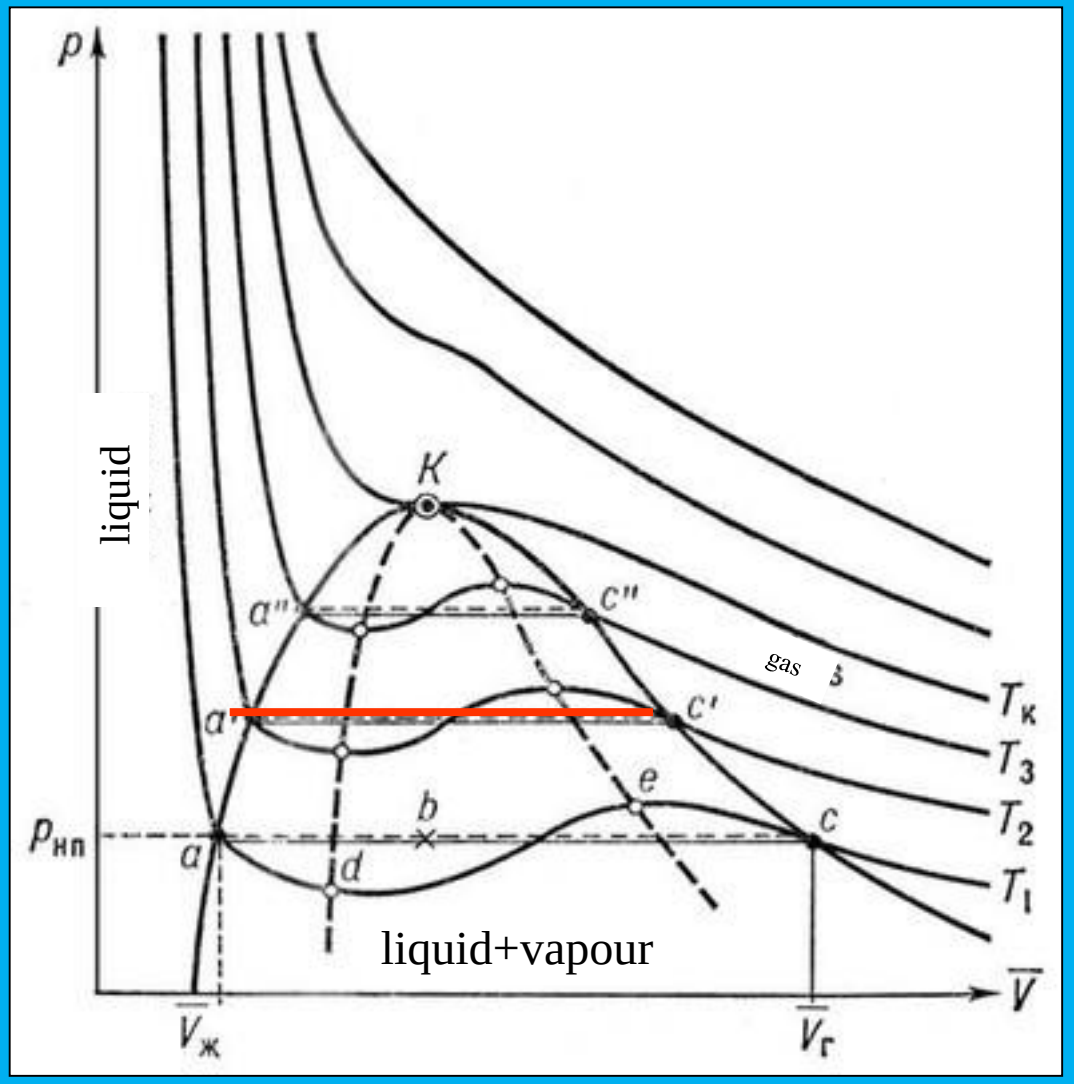
One-component matter
Maxwell-type PT

Phase coexistence conditions:

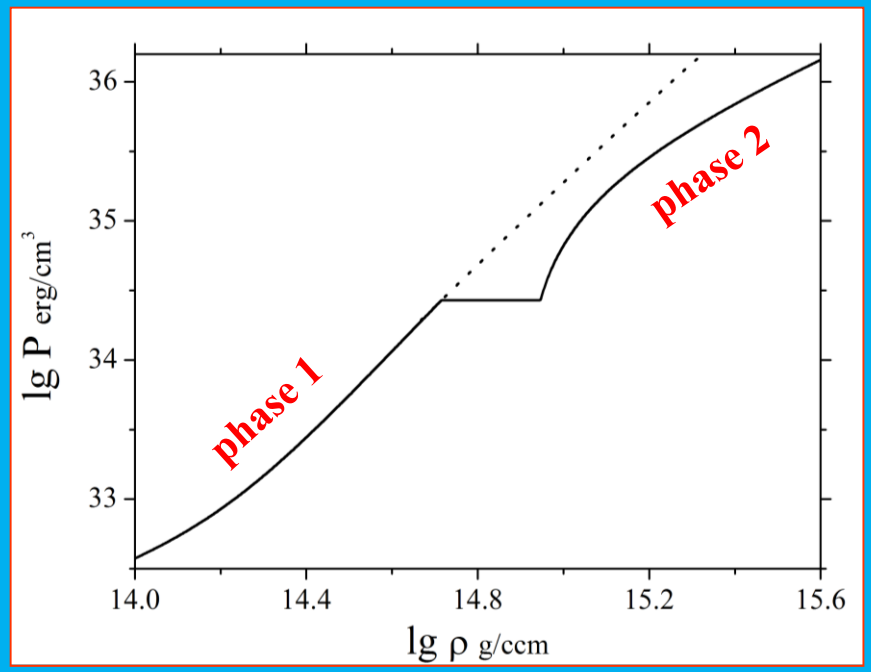
$$\begin{cases} P_I(\rho_I, T) = P_{II}(\rho_{II}, T) \\ \mu_I(\rho_I, T) = \mu_{II}(\rho_{II}, T) \end{cases}$$

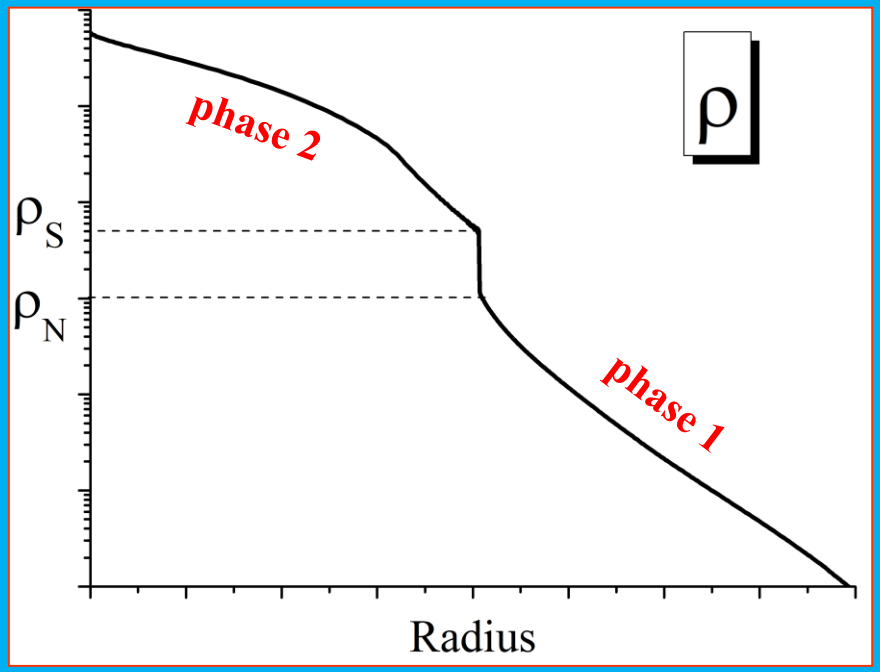
$$\rho = \chi\rho_I + (1-\chi)\rho_{II}$$

$$\chi = \frac{V_I}{V}, \quad V = V_I + V_{II}$$



Maxwellian-type phase transition causes a density jump inside the star





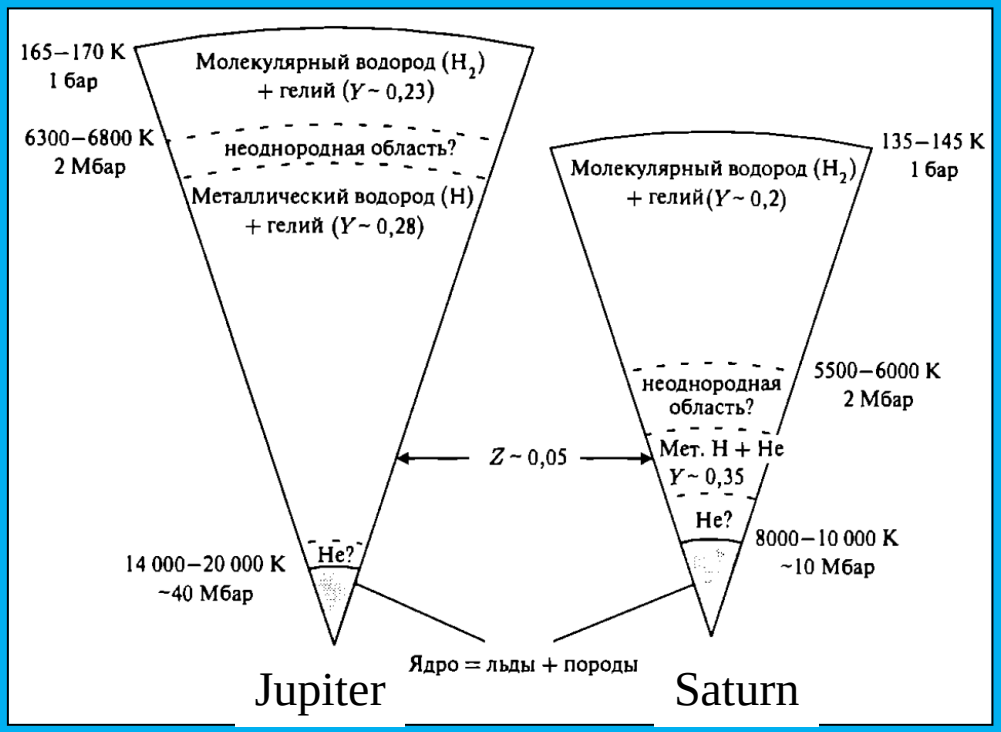
$$\lambda_c = \frac{\rho_S}{\rho_N} = \frac{3}{2}$$

W.H. Ramsey, MNRAS 110 (1950) 325
M.J. Lighthill, MNRAS 110 (1950) 339

$$\lambda^{rel} = \frac{\varepsilon_2}{\varepsilon_1}$$

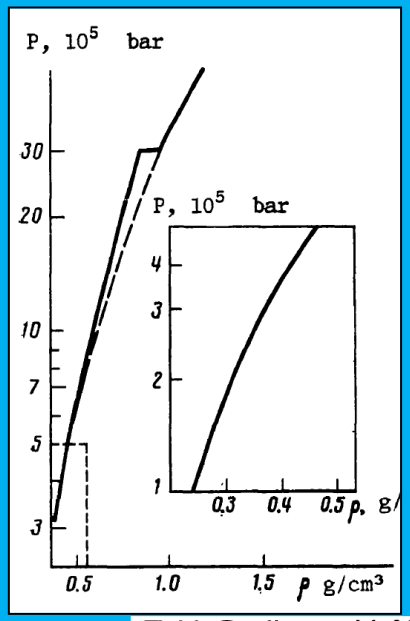
$$\lambda_c^{rel} = \frac{3}{2}\left(1 + \frac{P_*}{\varepsilon_1}\right)$$

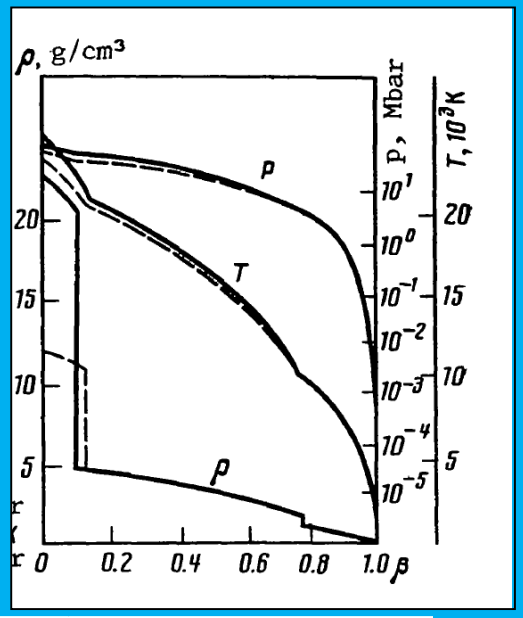
Z.F. Seidov (1971)



Giant Planets and (may be?) Brown Dwarfs

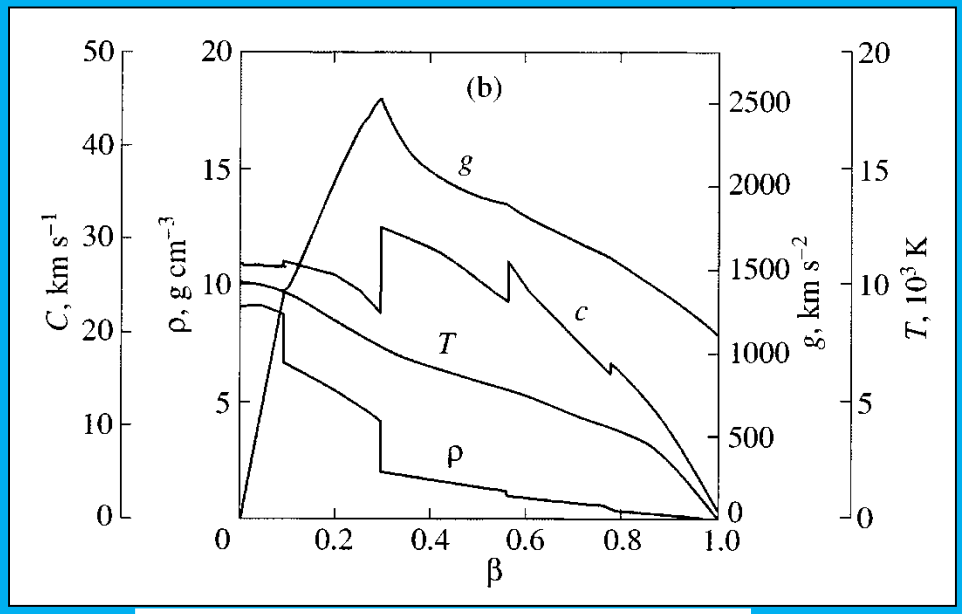
From "Systems of Jupiter and Saturn" by Kuskov, Dorofeeva, Kronrod and Makalkin URSS 2009 (on russian)





T. V. Gudkova, V. N. Zharkov, and V. V. Leont'ev

Soviet Astronomy Letters, Vol.14, NO. 2/MAR, P. 157, 1988

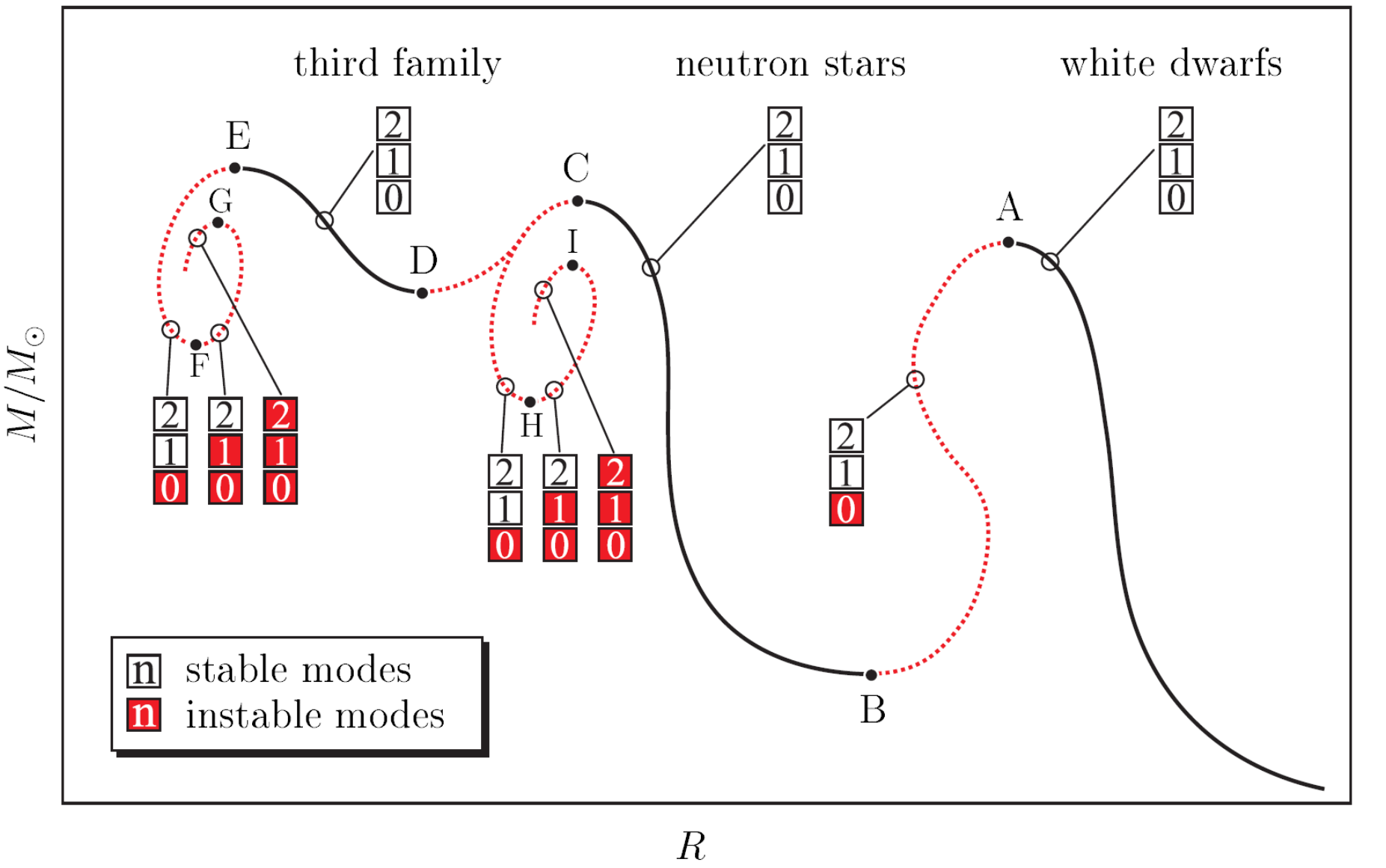


T. V. Gudkova* and V. N. Zharkov

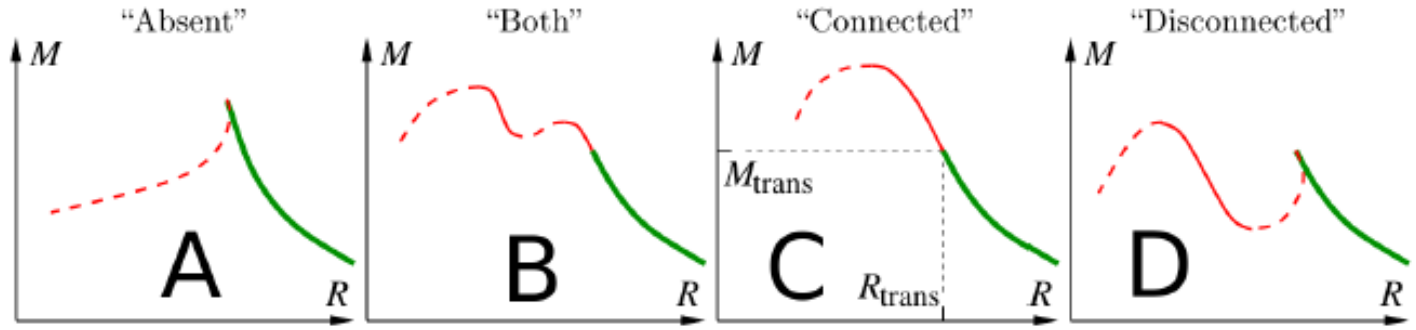
Astronomy Letters, Vol. 29, No. 10, 2003, pp. 674–694.

Quark phases in neutron stars and a "third family" of compact stars as a signature for phase transitions*

K. Schertler[a], C. Greiner[a], J. Schaffner-Bielich[b], and M.H. Thoma[c,†]



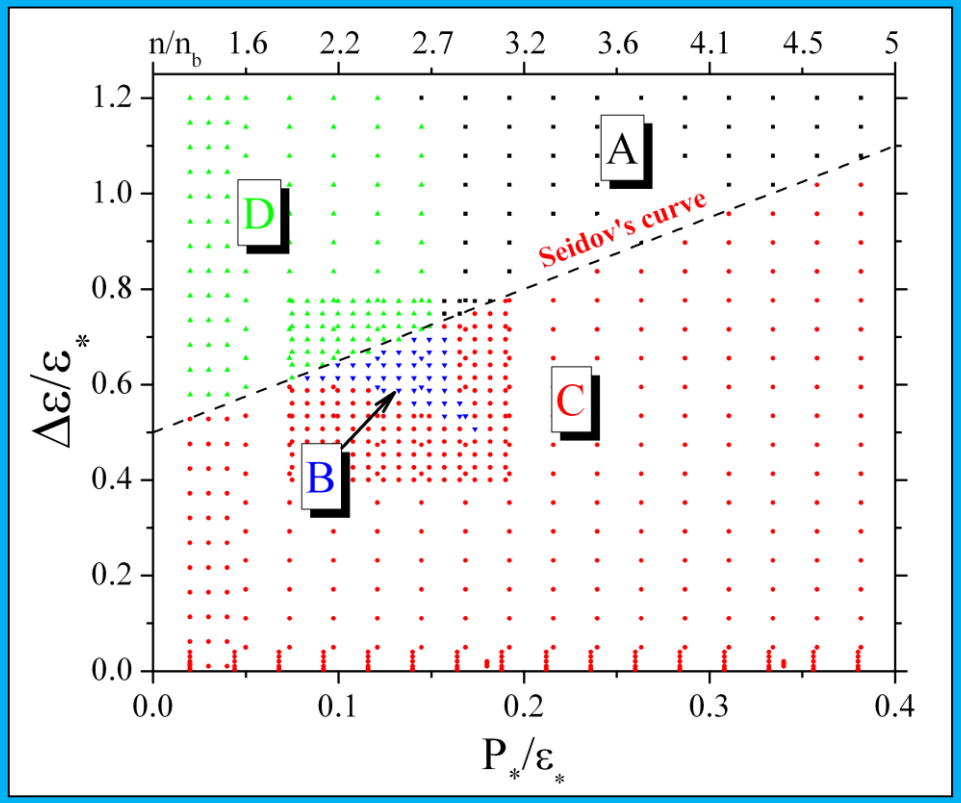
Mass-Radius relations for hybrid stars



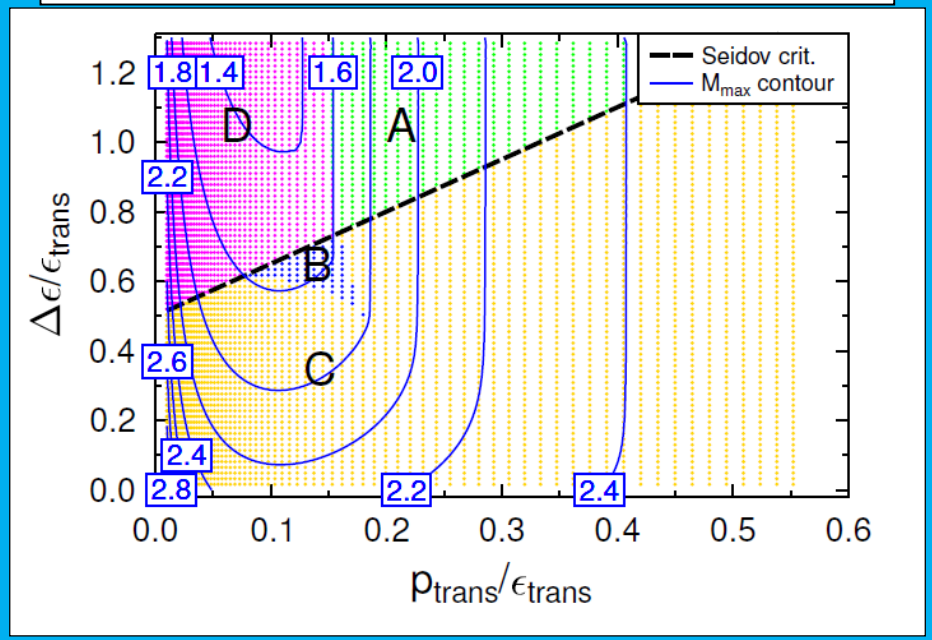
M. G. Alford, S. Han, and M. Prakash, Phys. Rev. D **88**, 083013 (2013).

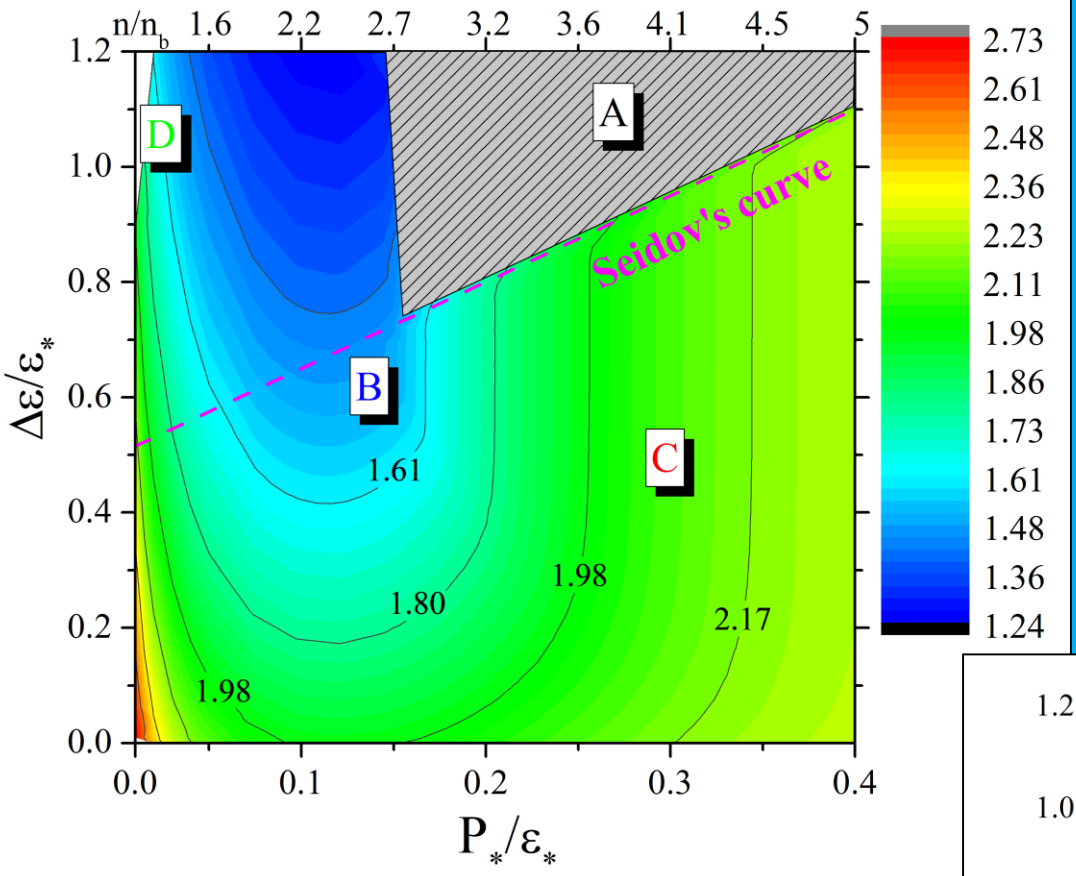
$$\lambda^{rel} = \frac{\varepsilon_2}{\varepsilon_1}$$

$$\lambda_c^{rel} = \frac{3}{2}\left(1+\frac{P_*}{\varepsilon_1}\right)$$



Heinimann, Hempel, Thielemann, Physical Review D, 94, 10, 2016





LETTER

doi:10.1038/nature09466

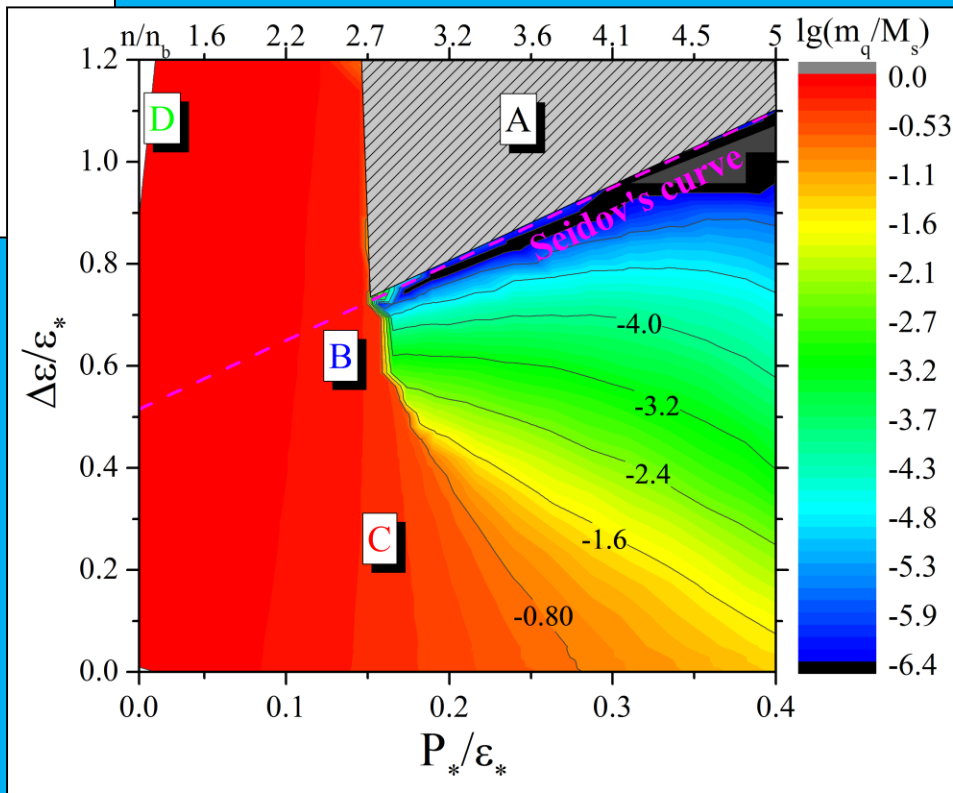
A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

$(1.97 \pm 0.04) M_{\odot}$

Maximum mass Ms level lines

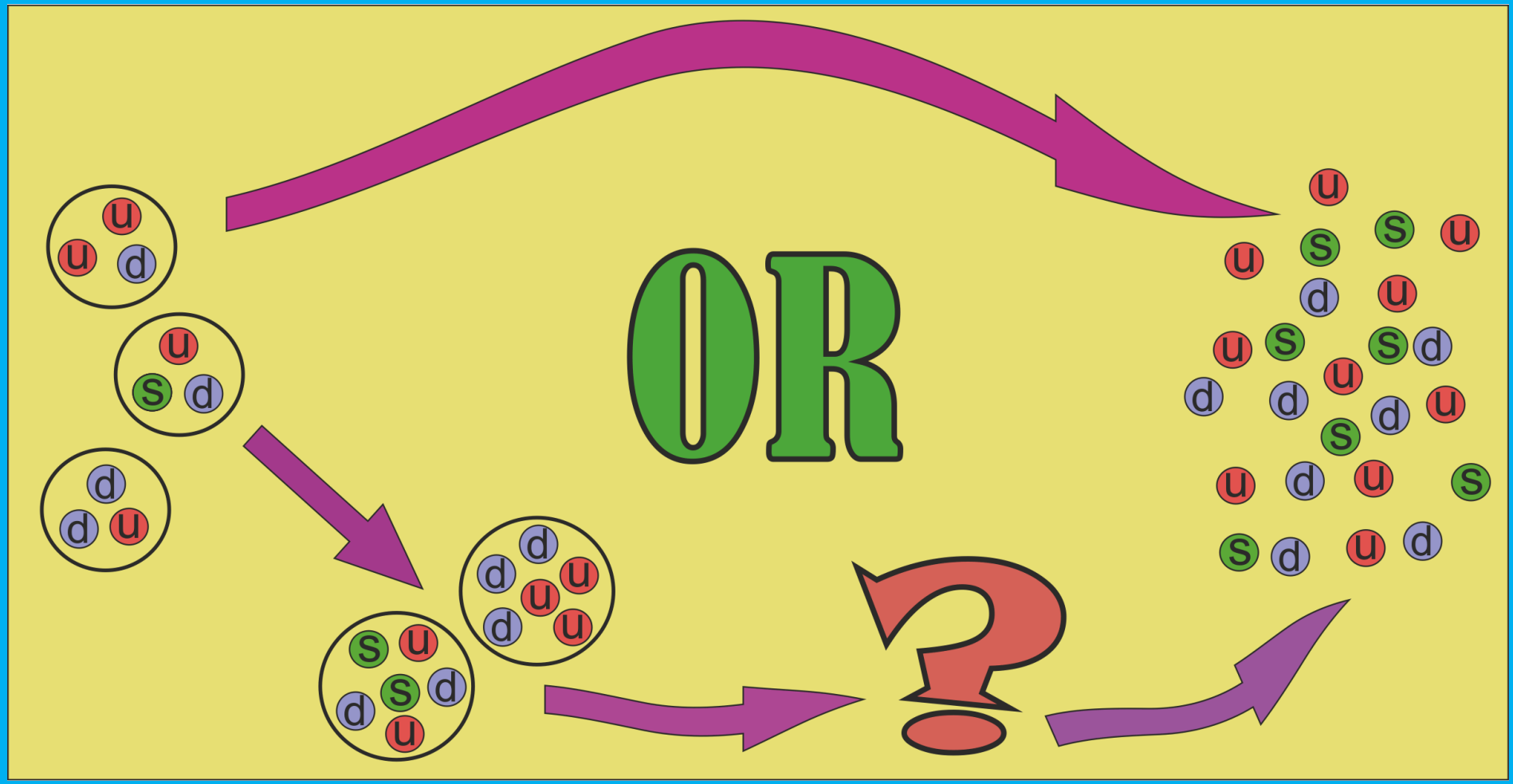
Log of mass fraction of quark core log(mq/Ms) level lines



Phase transition from nuclear to quark matter: is it a single strong event or a series of weaker transitions?

NUCLEAR MATTER AT HIGH DENSITY: PHASE TRANSITIONS, MULTIQUARK STATES, AND SUPERNOVA OUTBURSTS

© 2011 M. I. Krivoruchenko, D. K. Nadyozhin, T. L. Rasinkova, Yu. A. Simonov, M. A. Trusov*, A. V. Yudin



Variational Principle

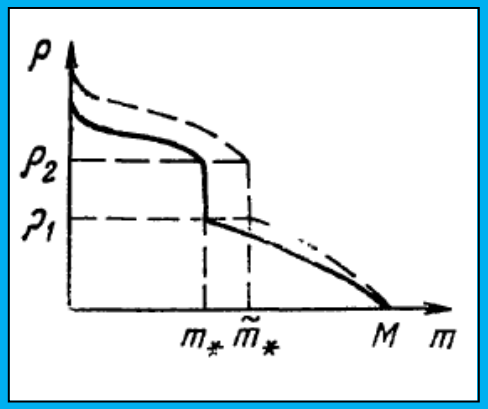
$$E_{tot} = E_{\text{int}} + W_G = \int \varepsilon_{\text{int}} dm - \int \frac{Gm}{r} dm = \min$$

Zel'dovich, Novikov "Relativistic Astrophysics"

$$\delta E_{tot} = 0, \qquad \delta^2 E_{tot} > 0$$

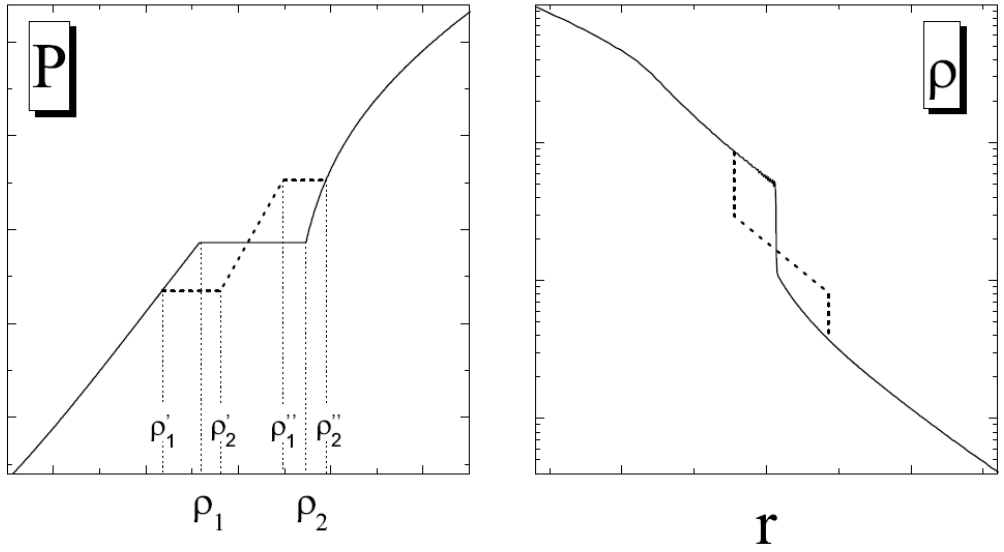
Bisnovatyi-Kogan, Blinnikov, Shnol Sov. Astron, 19, 559,1976

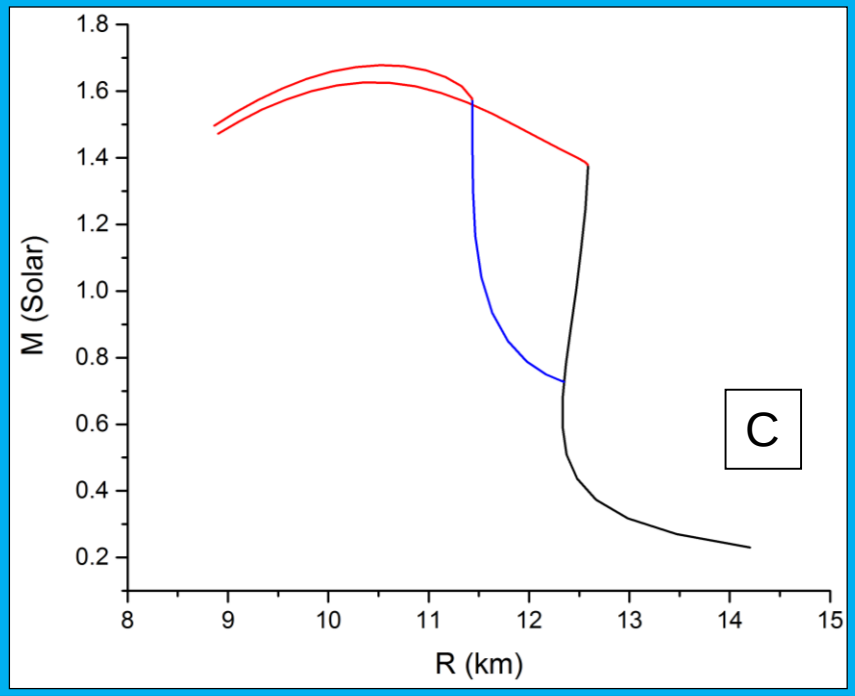
$$\mathbf{V} = \mathbf{V}_{\mathrm{I}} + \mathbf{V}_{\mathrm{O}} = \int_0^M \left[P\gamma\rho \left(\frac{d\varphi}{dm} \right)^2 - \frac{4\beta}{9} \frac{m\varphi^2}{\upsilon^{7/3}} \right] dm + \frac{\beta m_*}{3\upsilon_*^{4/3}} \frac{(\varphi_1 - \varphi_2)^2}{\frac{1}{\rho_1} - \frac{1}{\rho_2}} > 0,$$

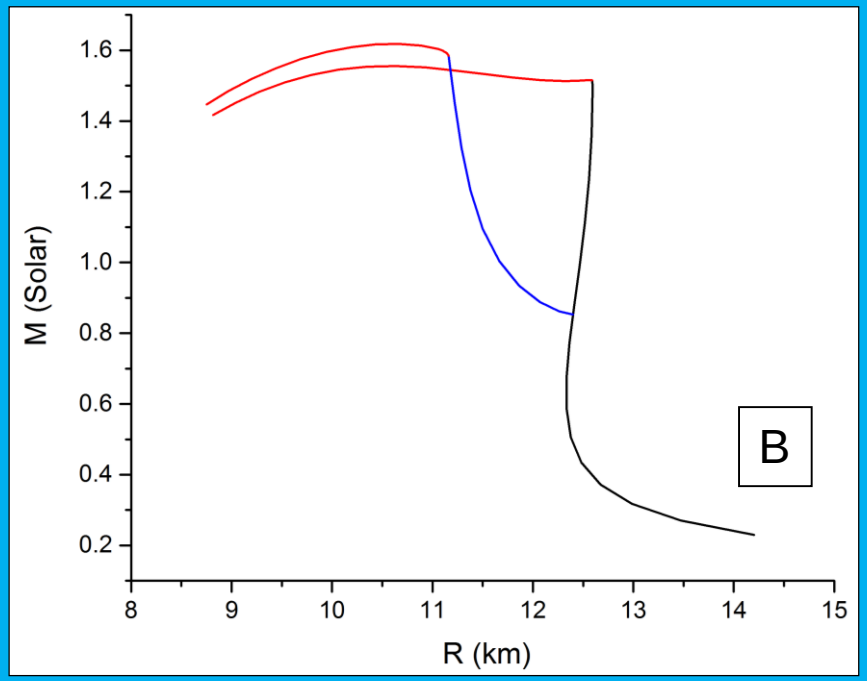


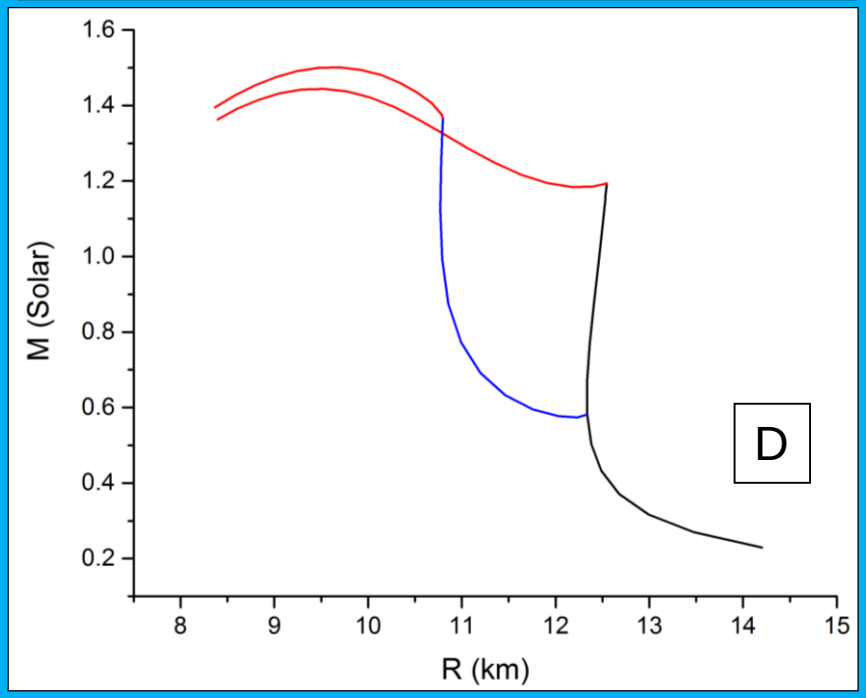
$$\frac{\rho_2}{\rho_1} < \frac{3}{2}.$$

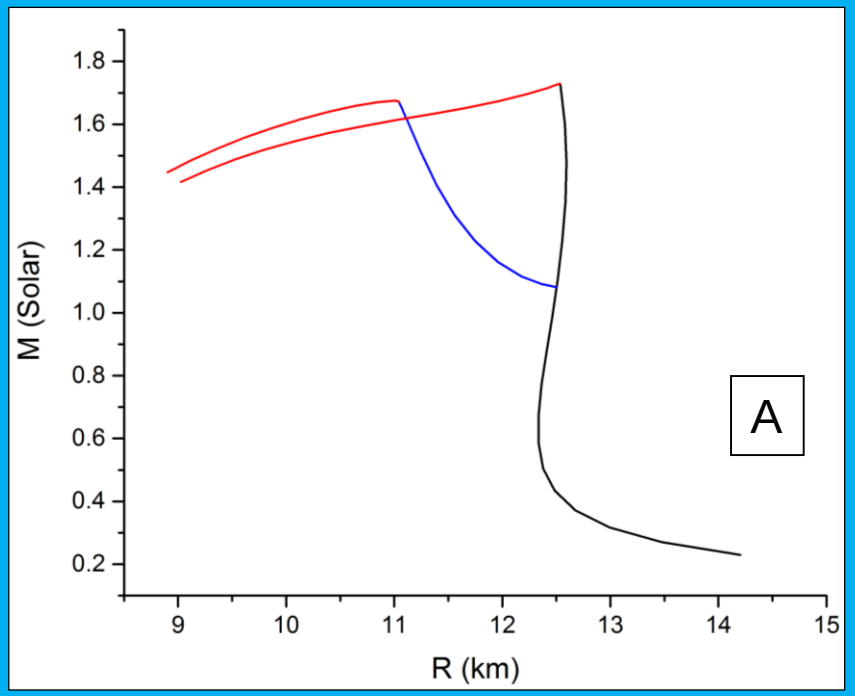
$$\mathbf{V}'_{\mathrm{O}} \propto \frac{(\varphi_1 - \varphi_3)^2}{\frac{1}{\rho_1} - \frac{1}{\rho'_2}} + \frac{(\varphi_3 - \varphi_2)^2}{\frac{1}{\rho''_1} - \frac{1}{\rho_2}} \geq \frac{(\varphi_1 - \varphi_2)^2}{\frac{1}{\rho_1} - \frac{1}{\rho_2}}$$

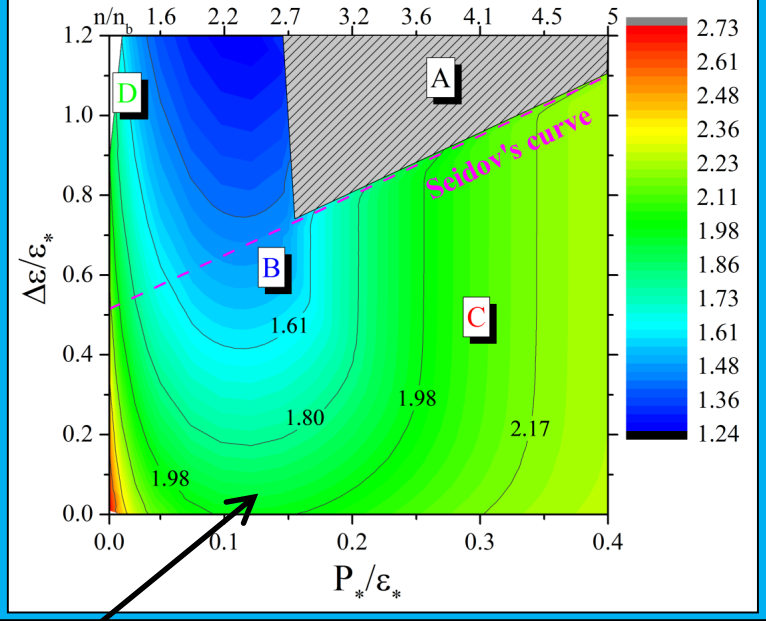


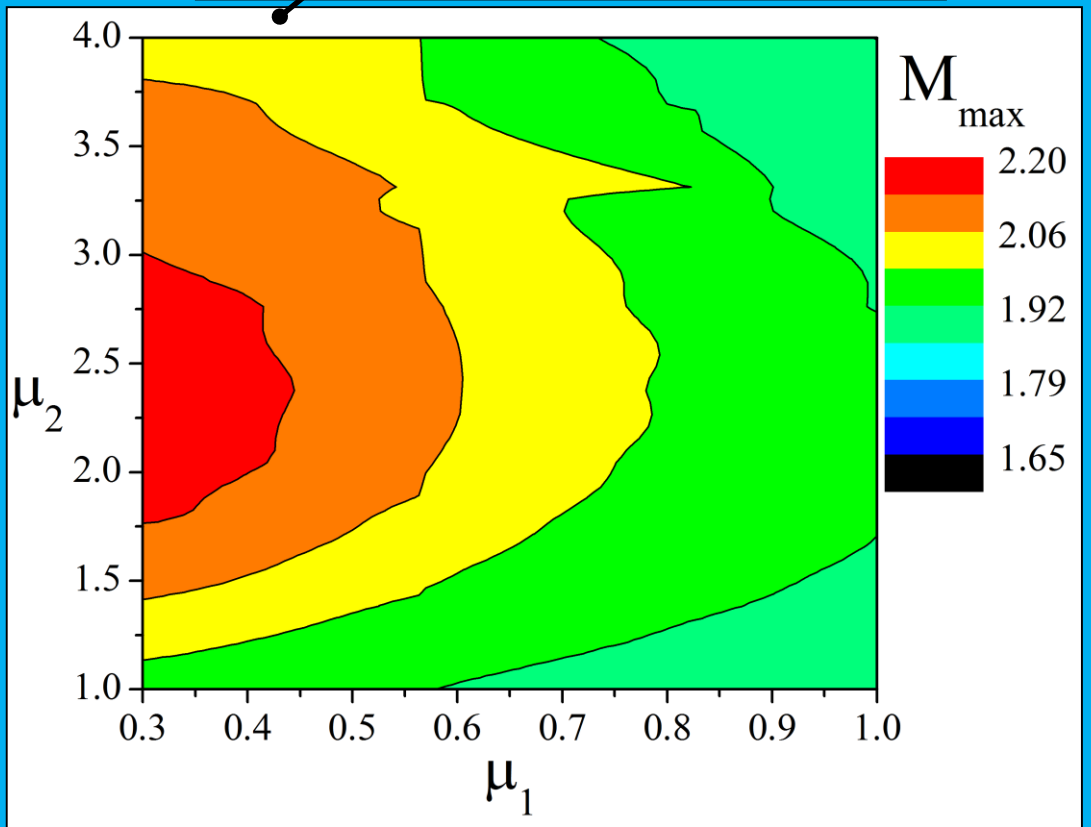

M (Solar)
R (km)
C

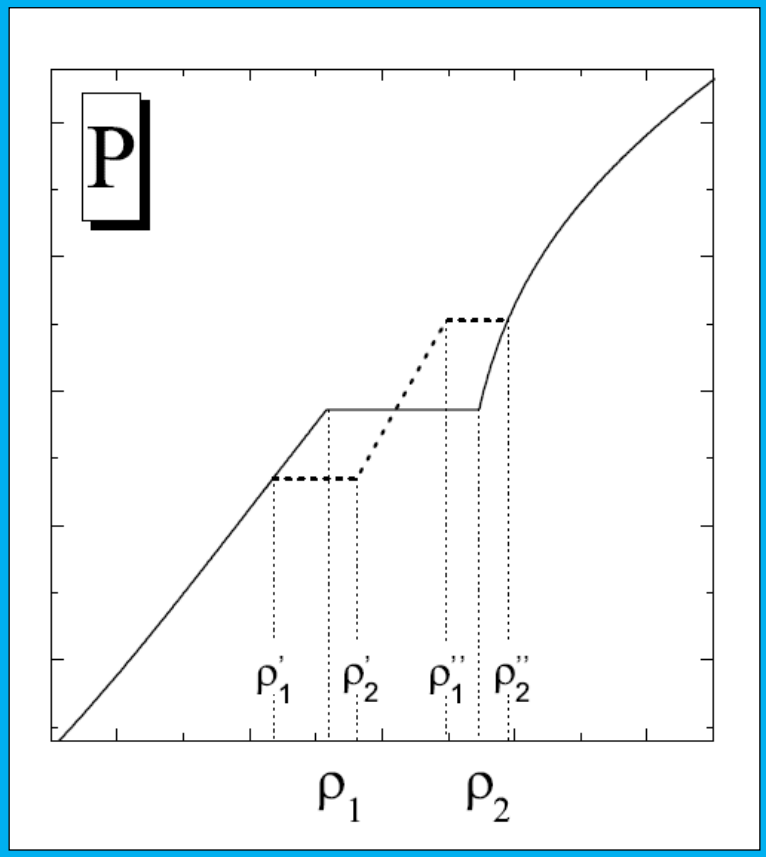

M (Solar)
R (km)
B


M (Solar)
R (km)
D


M (Solar)
R (km)
A



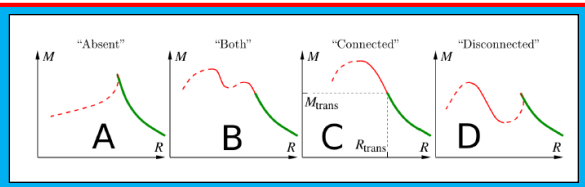




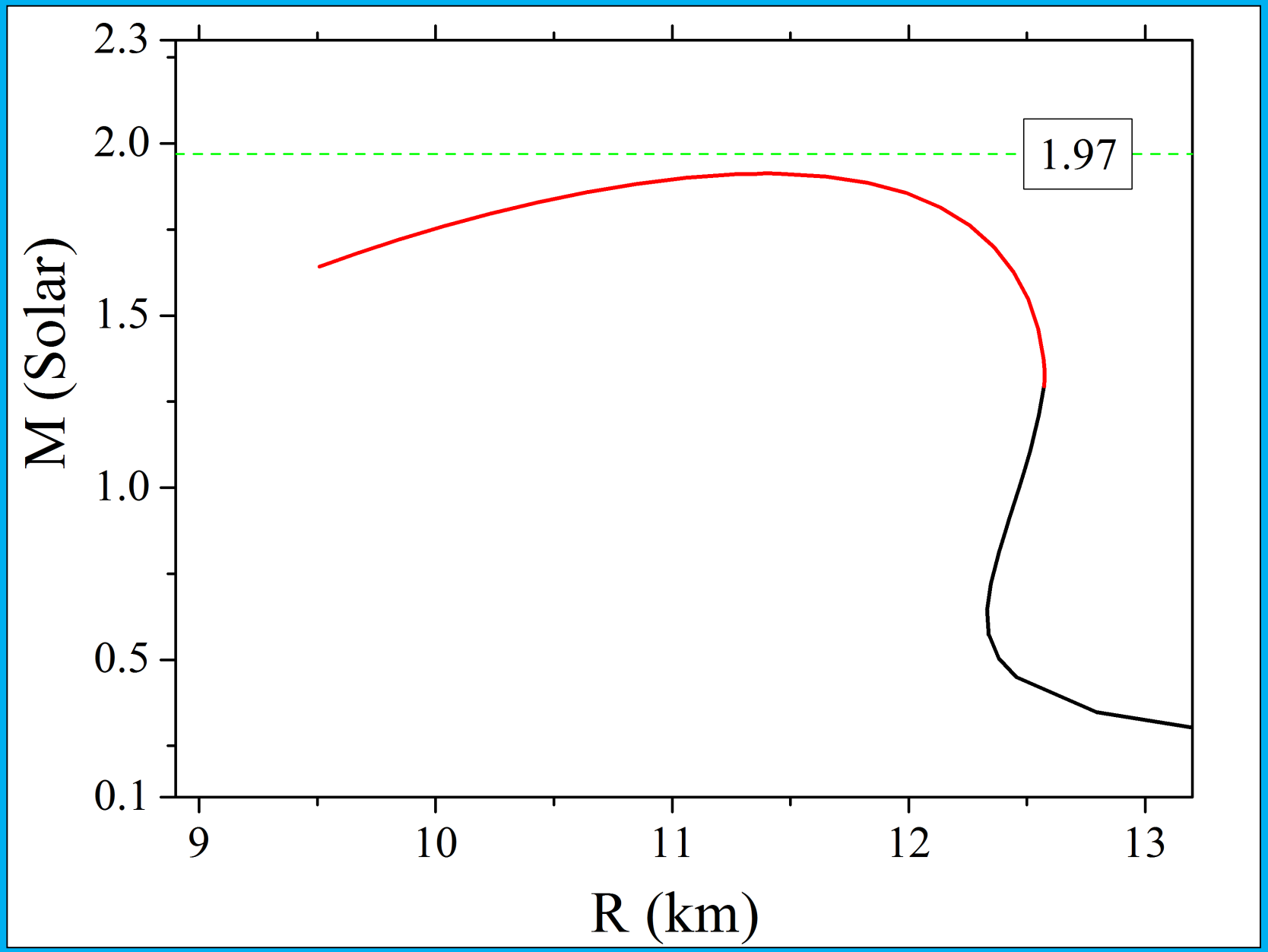
$$\rho_1' = \rho_1 \times \mu_1, \quad \mu_1 \le 1$$

$$\rho_2'' = \rho_2 \times \mu_2, \quad \mu_2 \ge 1$$

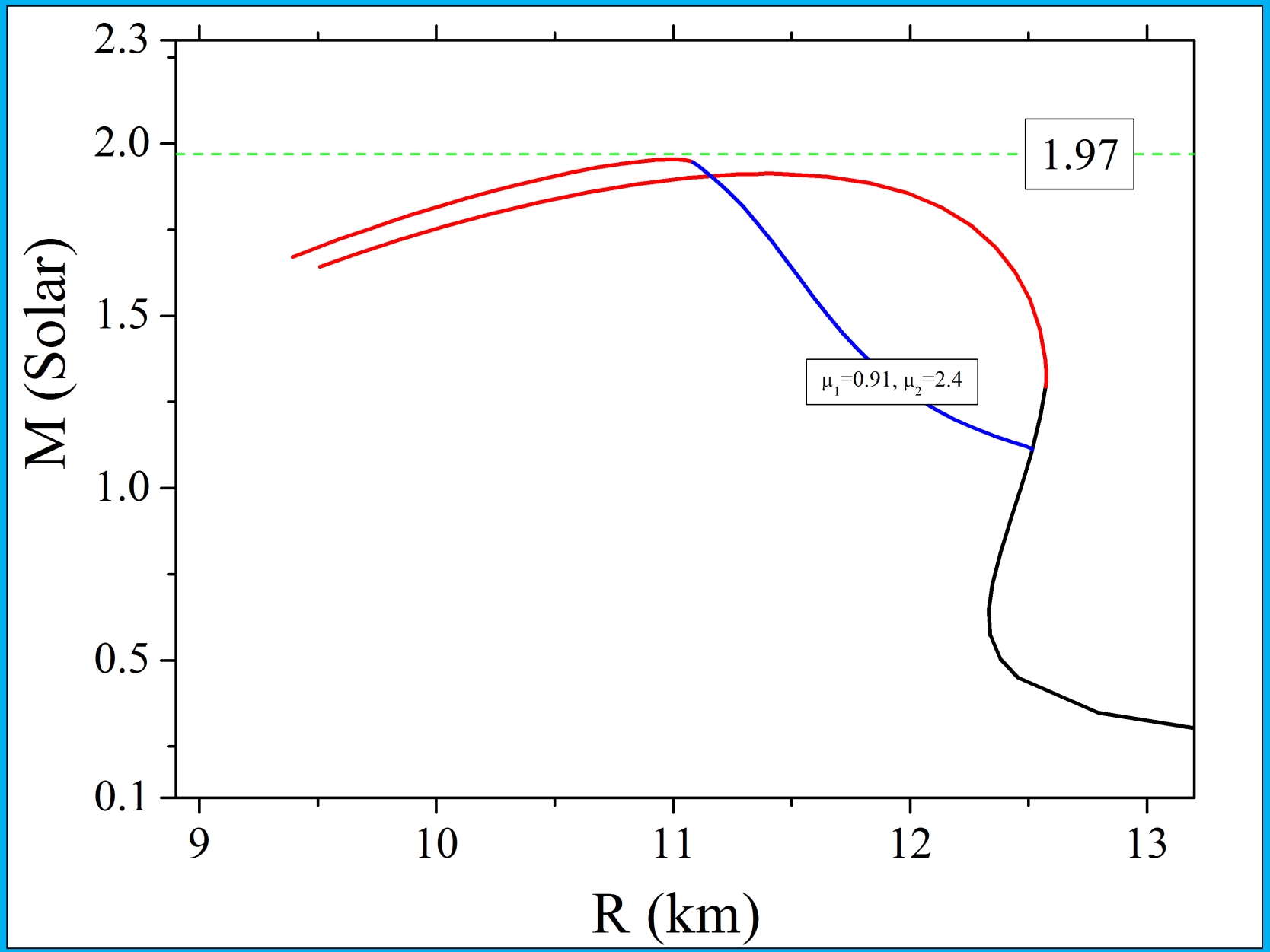
M_{max}(1PT)=1.91 M_{Sun}



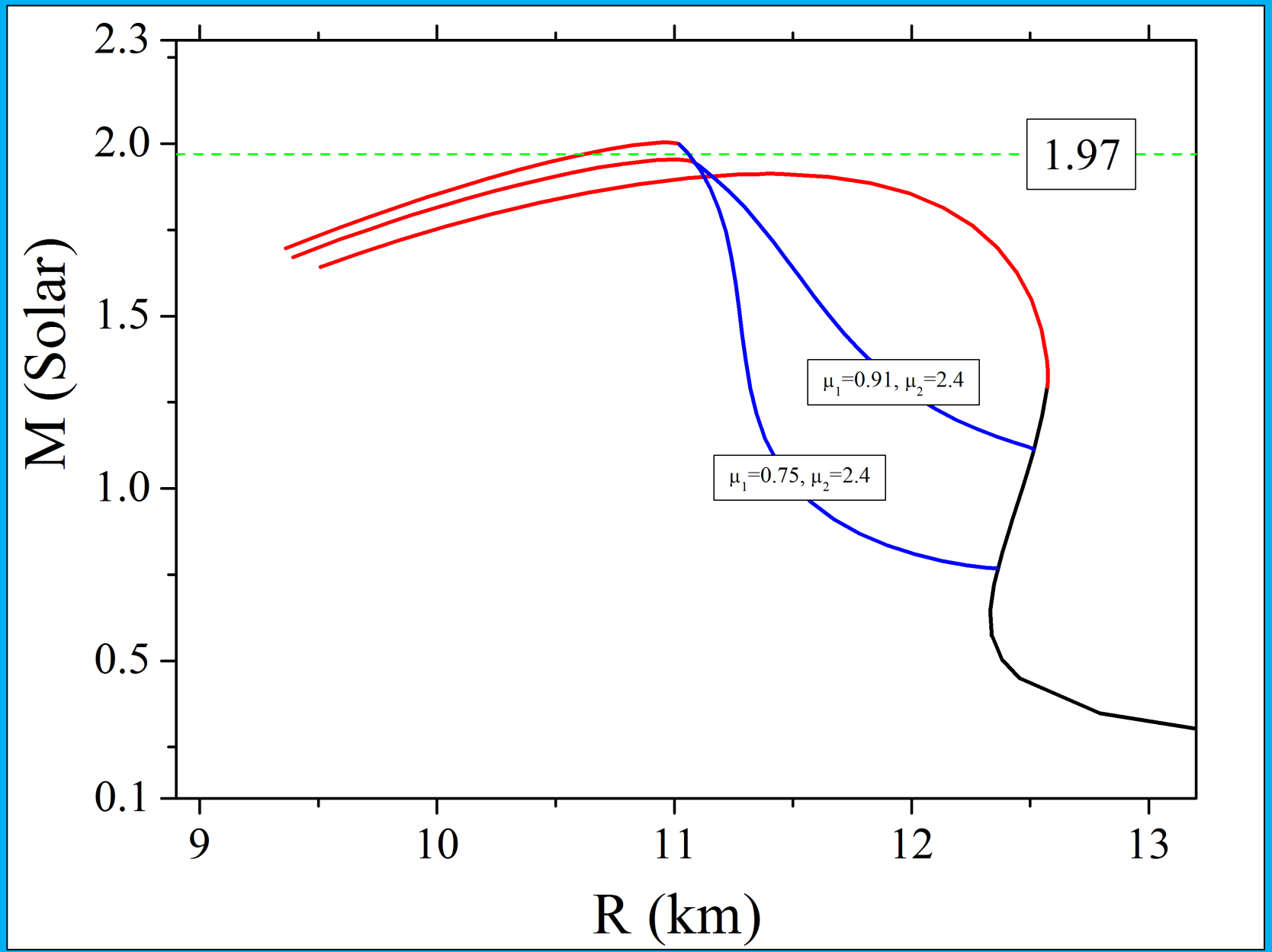
Mass-Radius relation



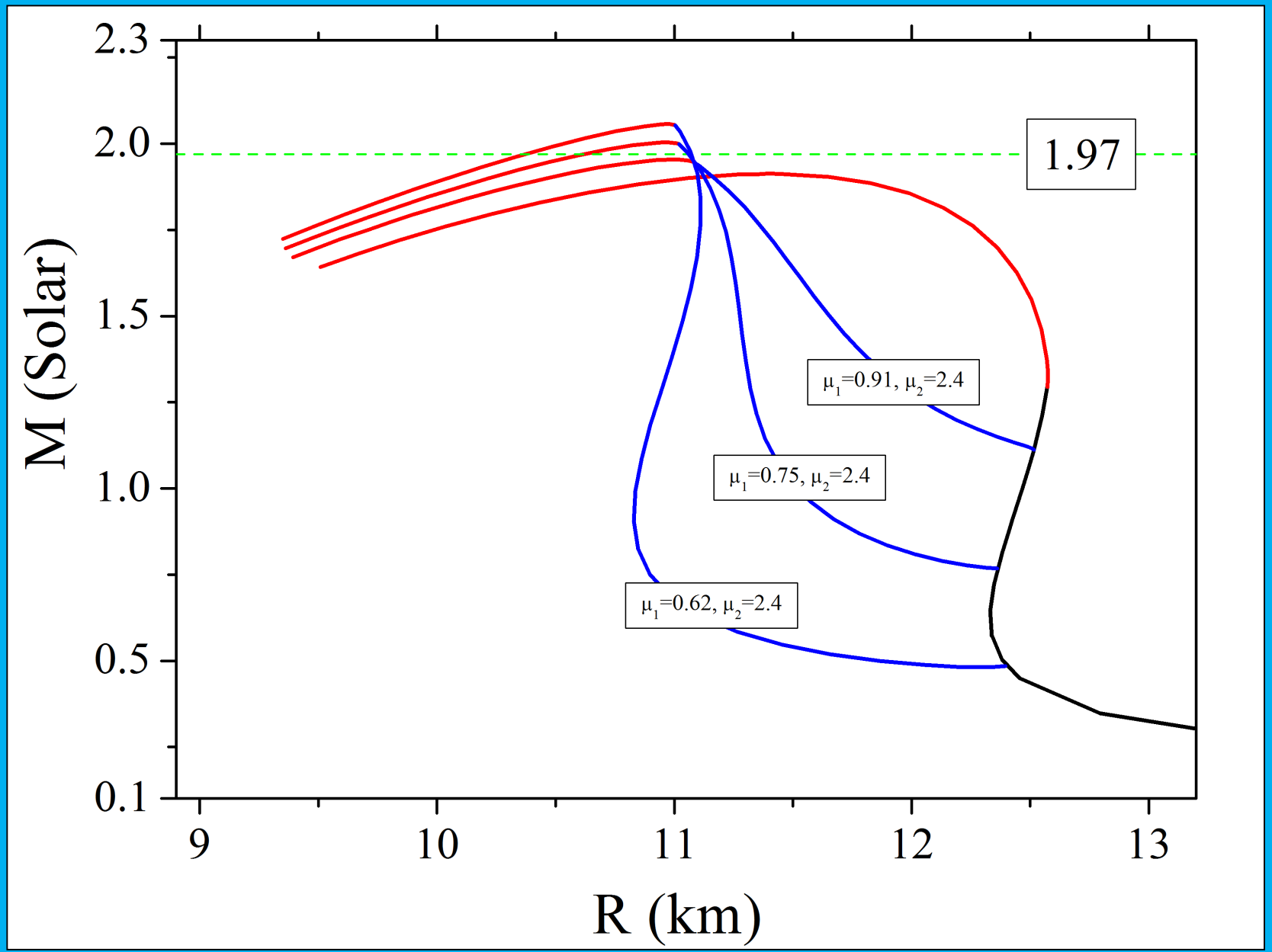
Mass-Radius relation



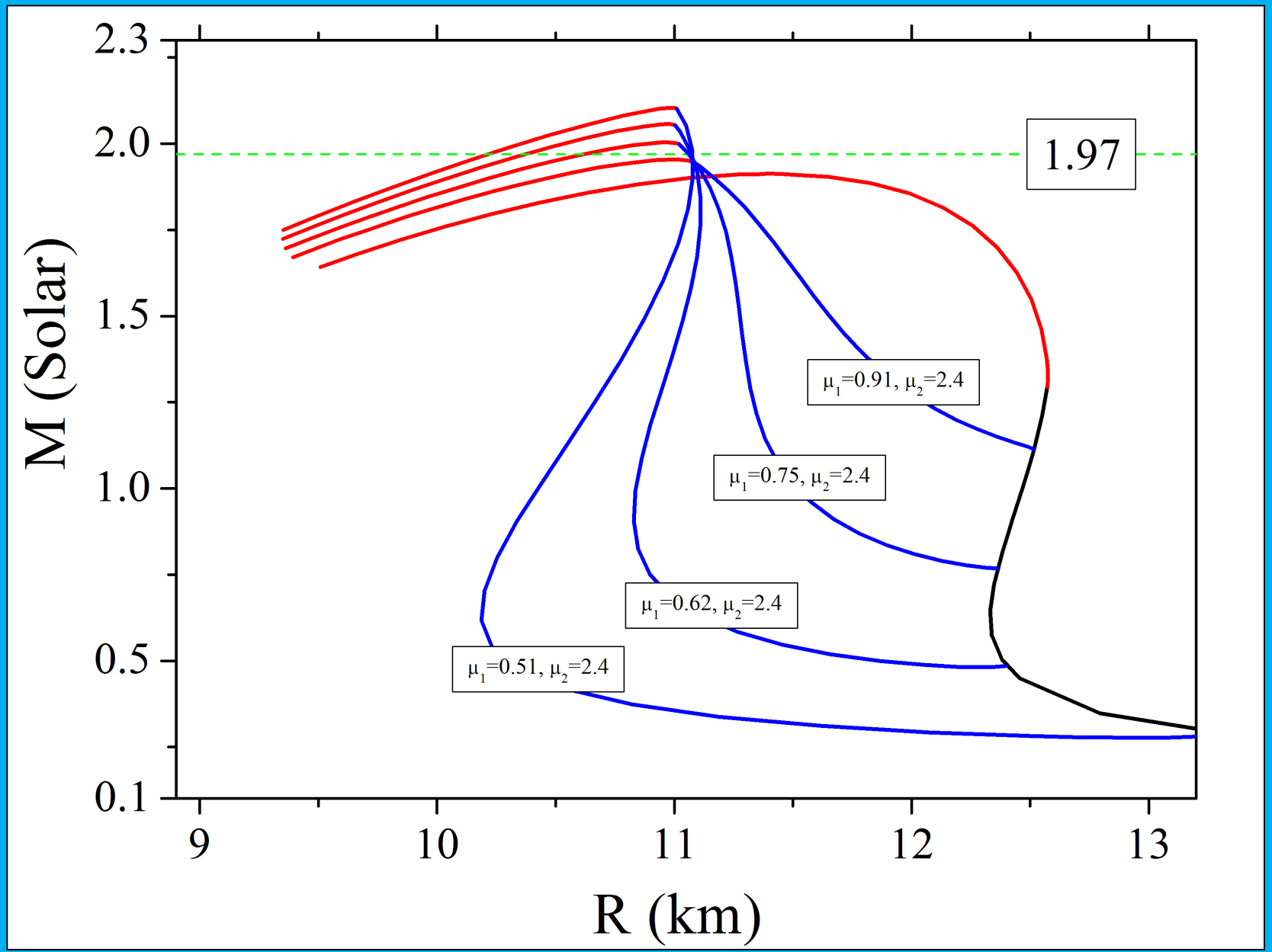
Mass-Radius relation



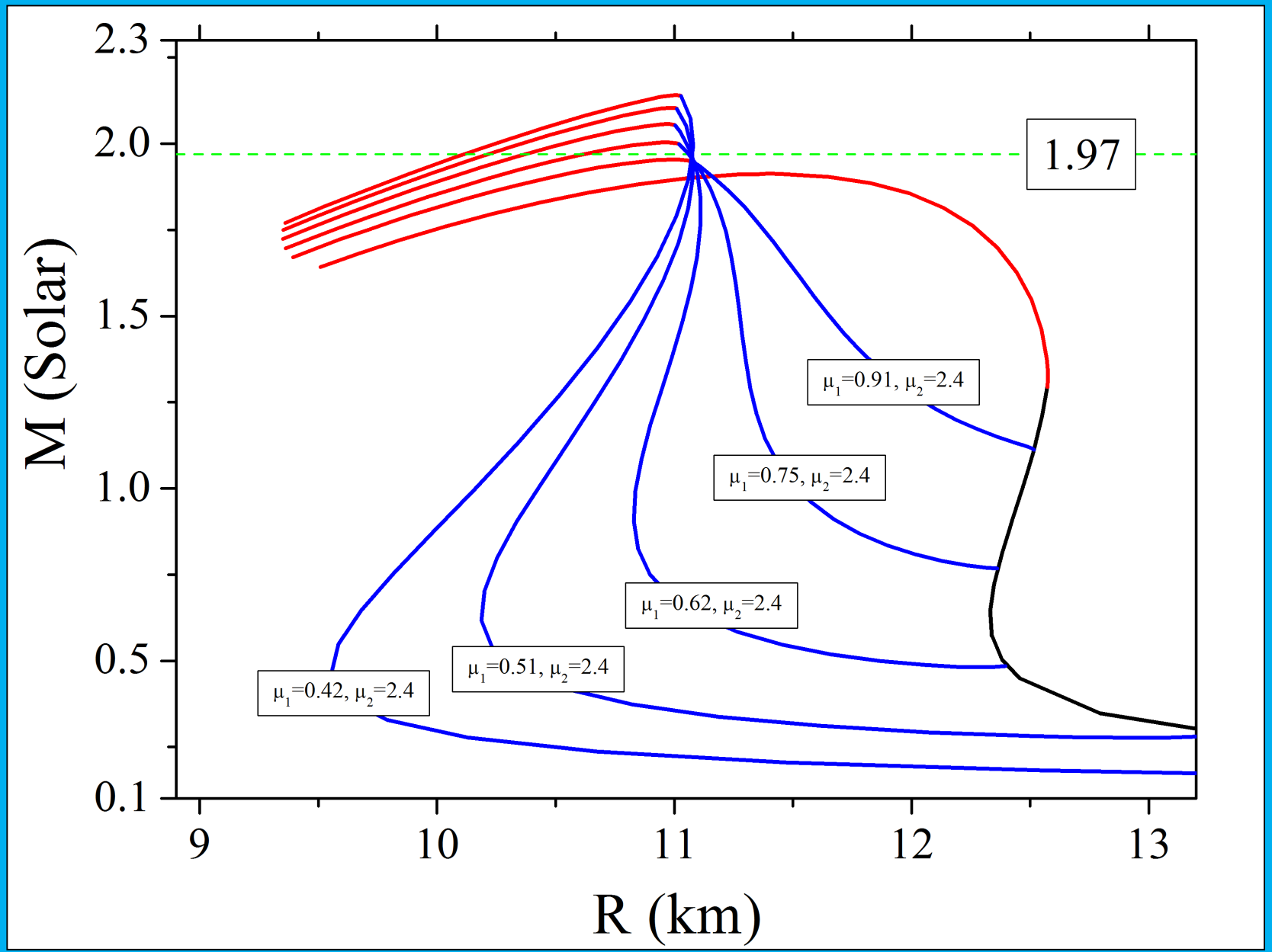
Mass-Radius relation



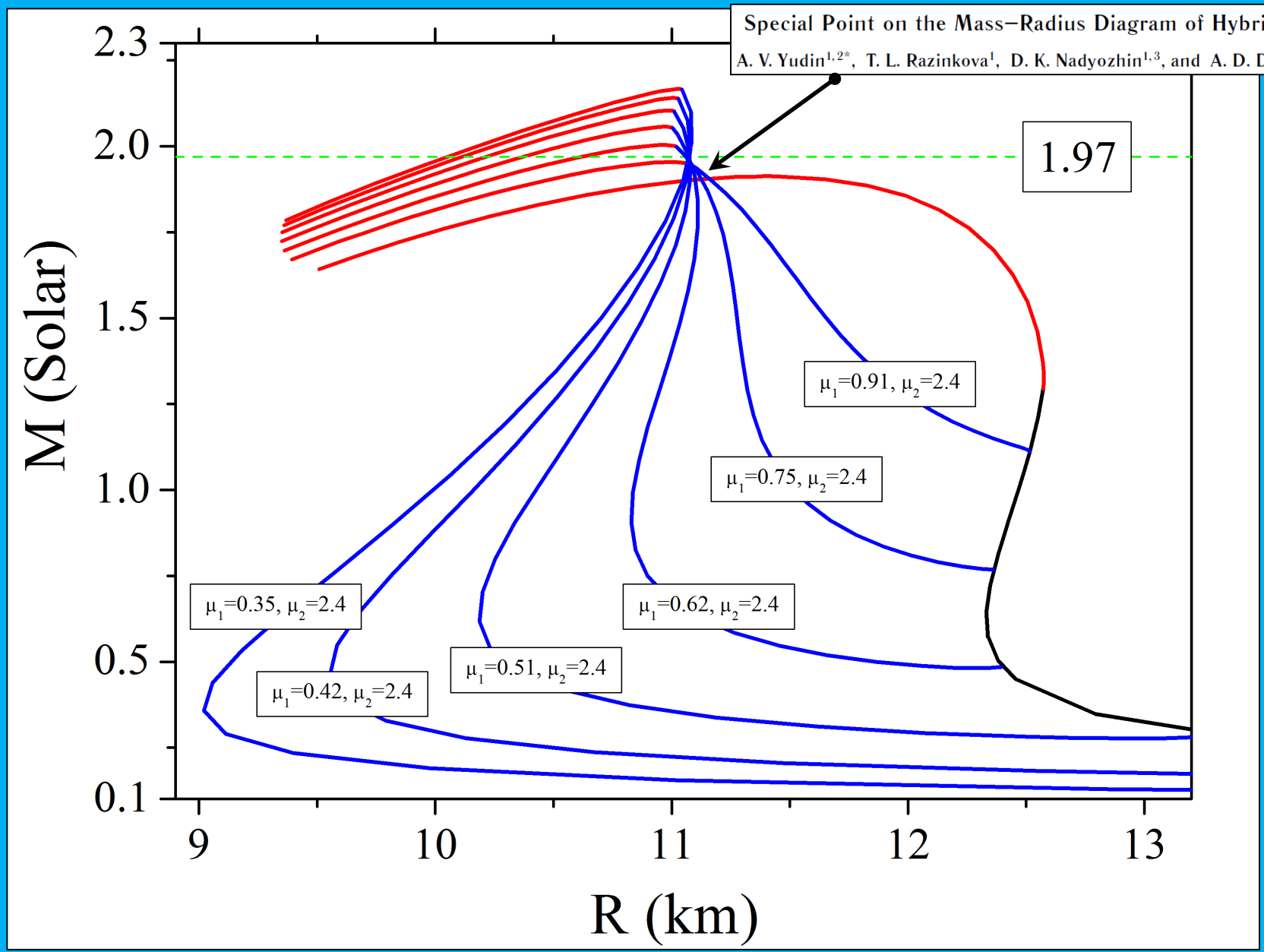
Mass-Radius relation

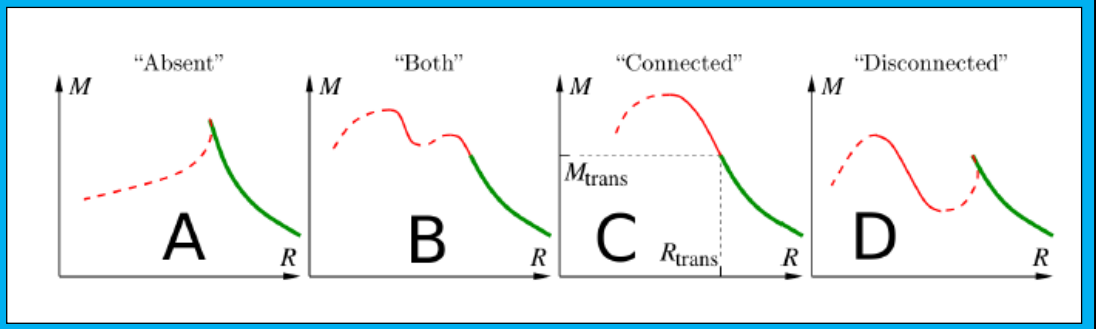


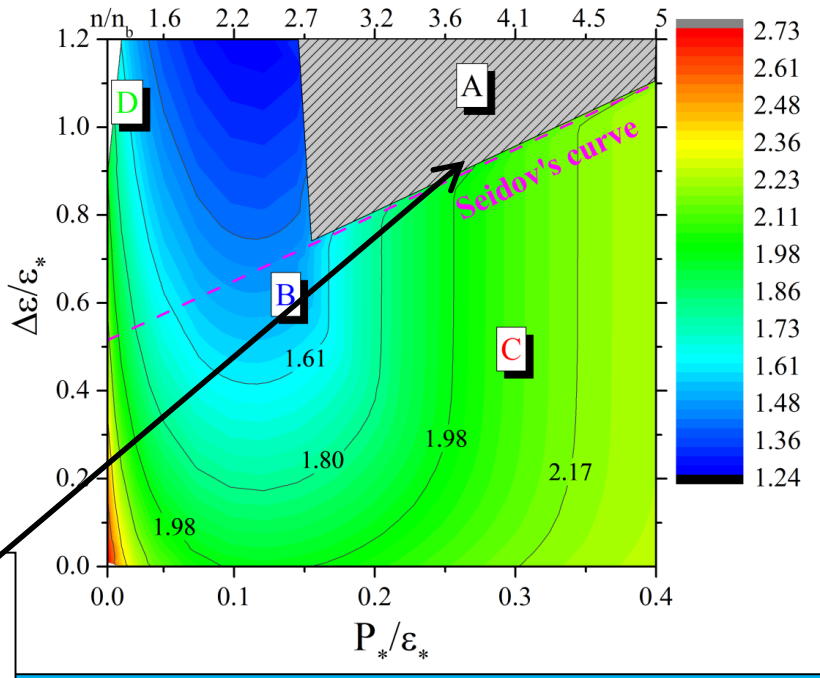
Mass-Radius relation

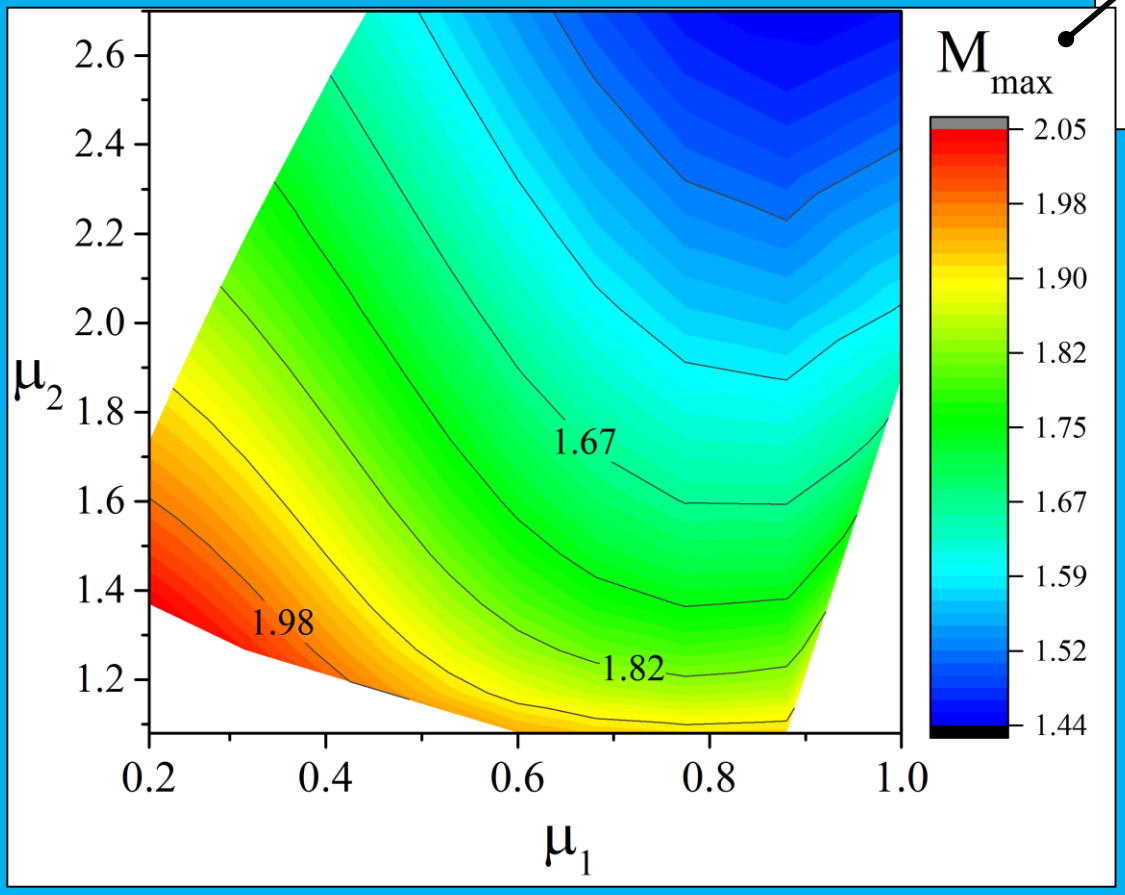


Mass-Radius relation



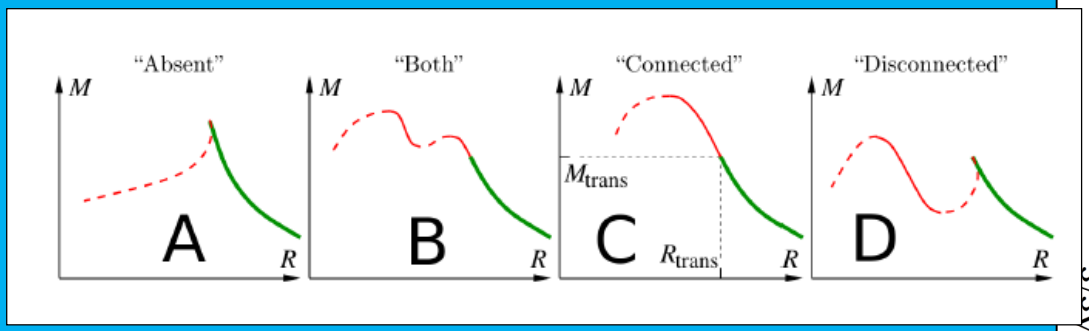




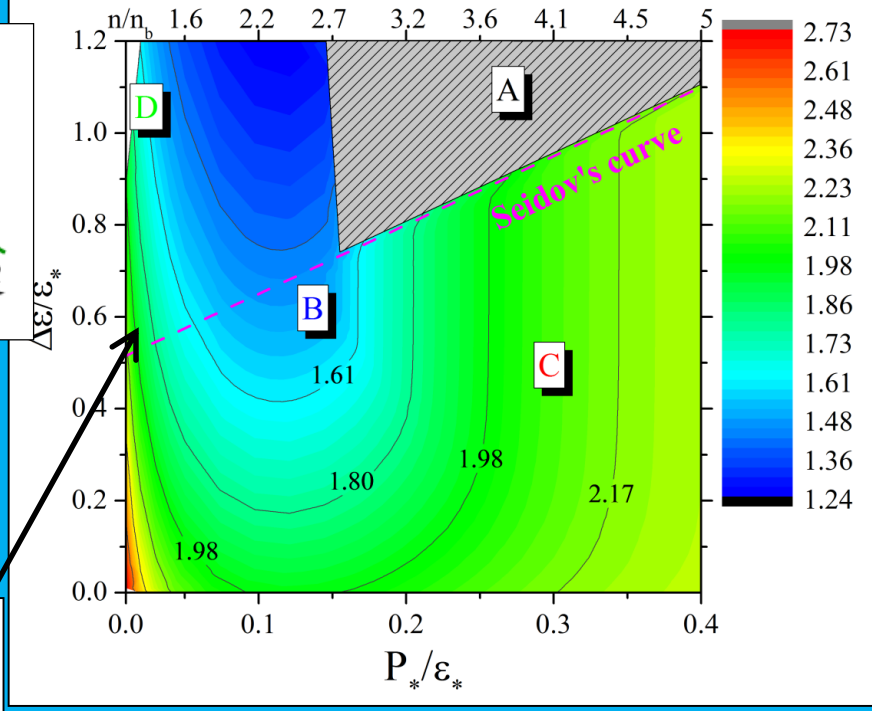


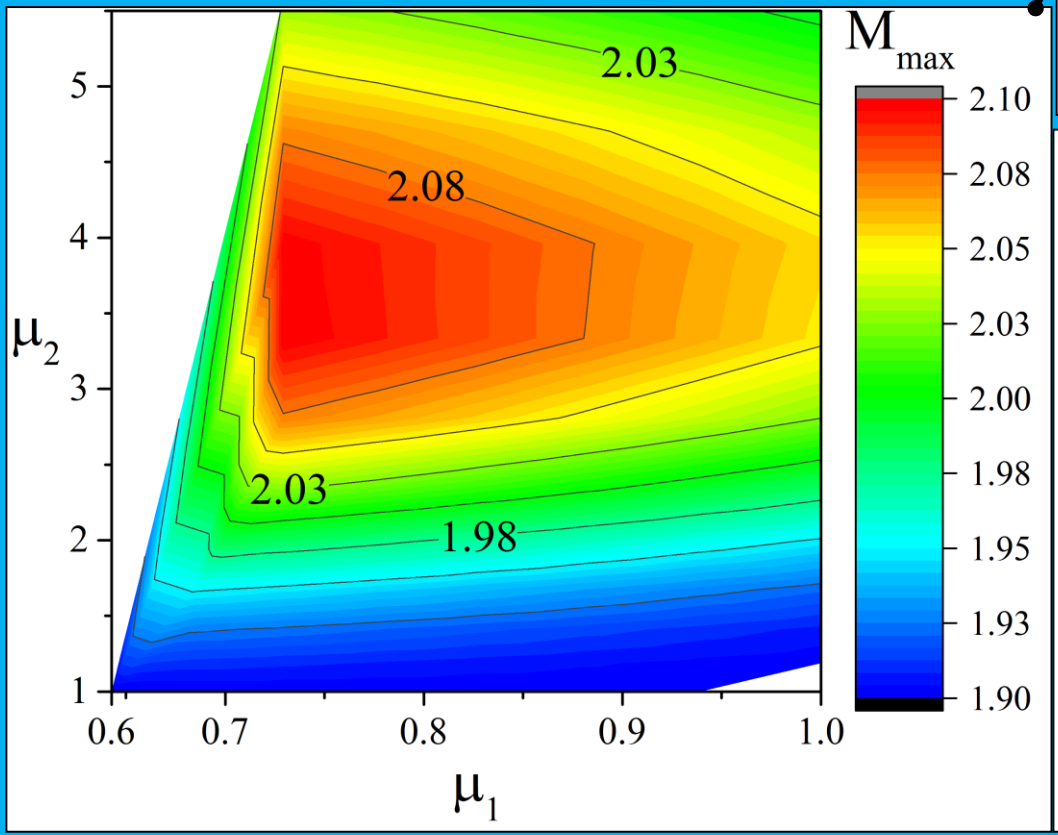
M_{max}(1PT)=2.0 M_{sun}

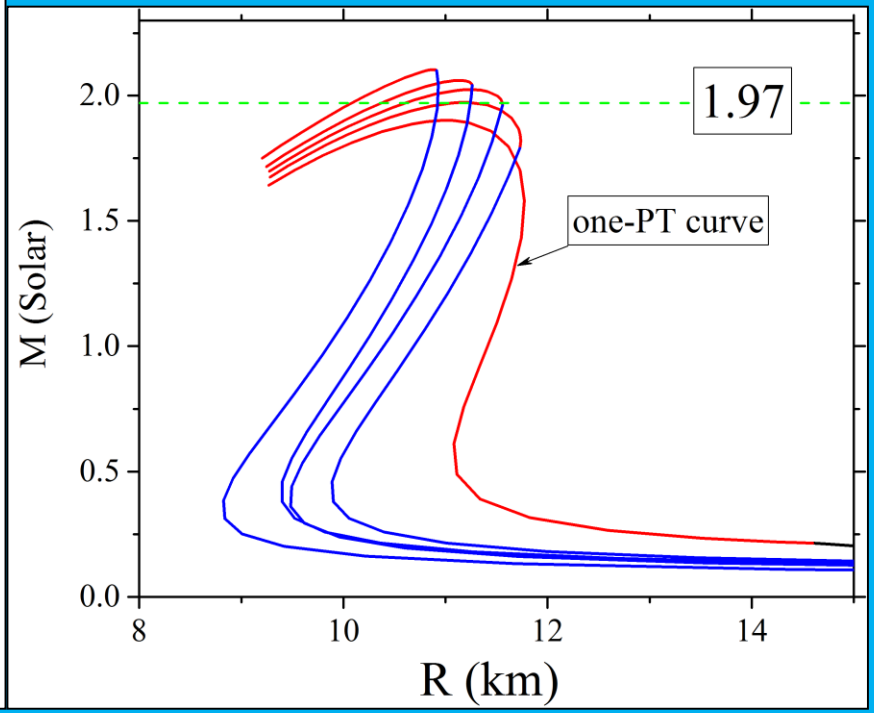
but no stable hybrid configurations!



M_{max}(1PT)=1.9 M_{sun}







Quark/hybrid stars

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]

The scenario of two families of compact stars

1. Equations of state, mass-radius relations and binary systems

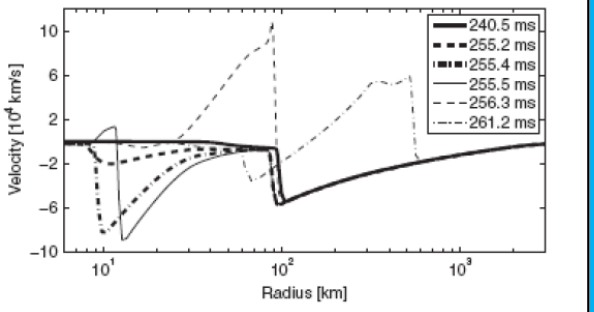
Alessandro Drago[1], Andrea Lavagno[2], Giuseppe Pagliara[1], and Daniele Pigato[2]

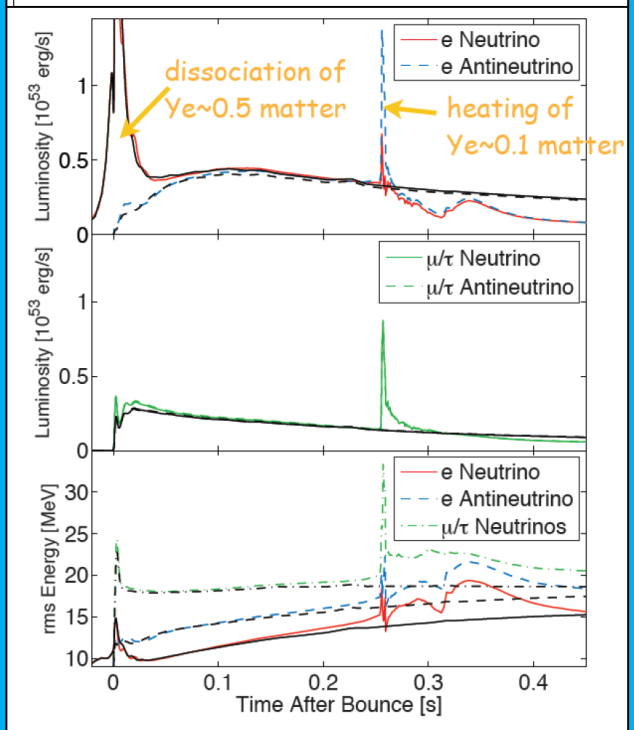
The scenario of two families of compact stars

2. Transition from hadronic to quark matter and explosive phenomena

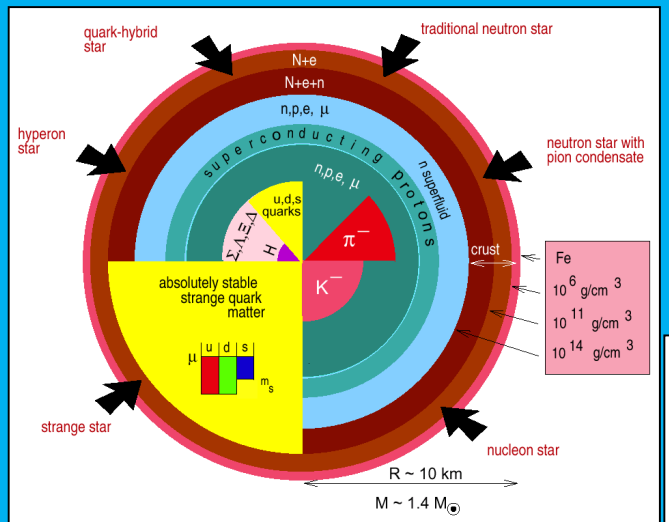
Alessandro Drago and Giuseppe Pagliara

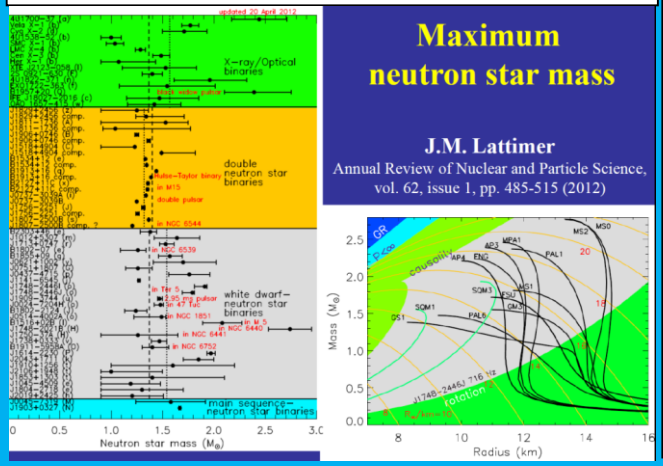
SN-hybrid star connection





Properties of compact stars



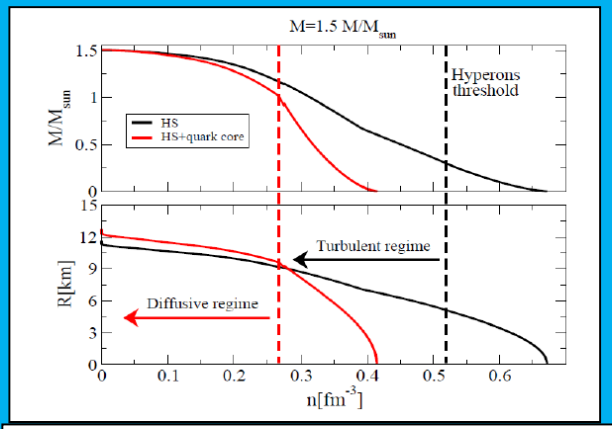


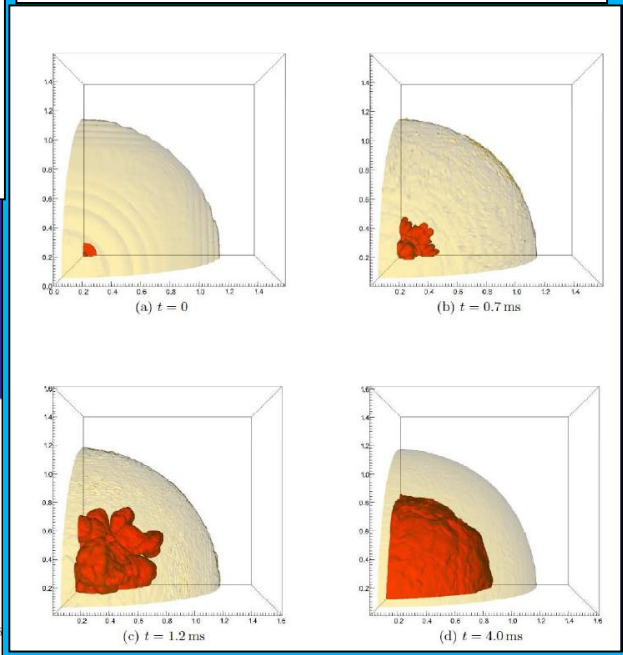
Maximum neutron star mass

J.M. Lattimer

Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 485-515 (2012)

Quark star formation

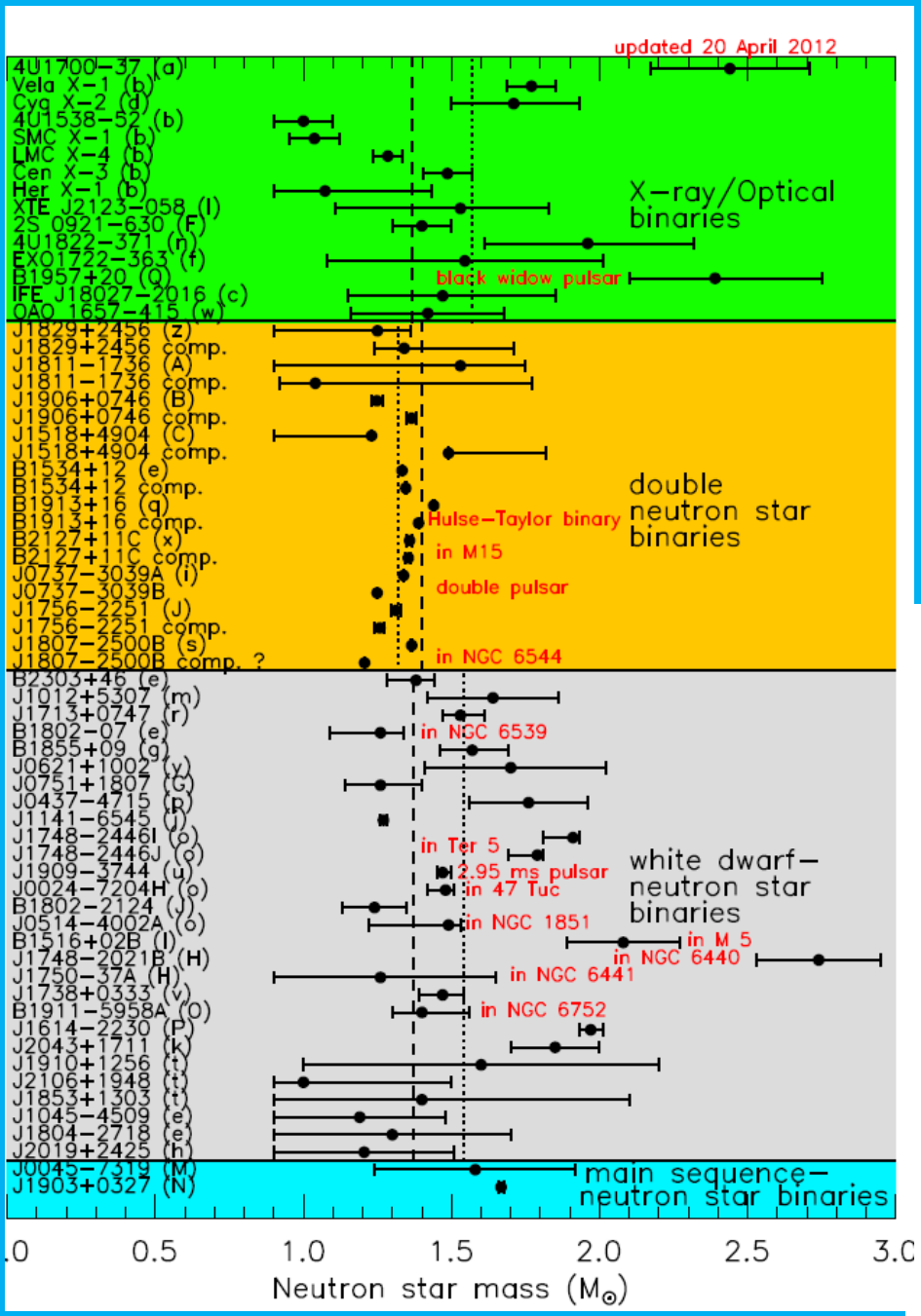


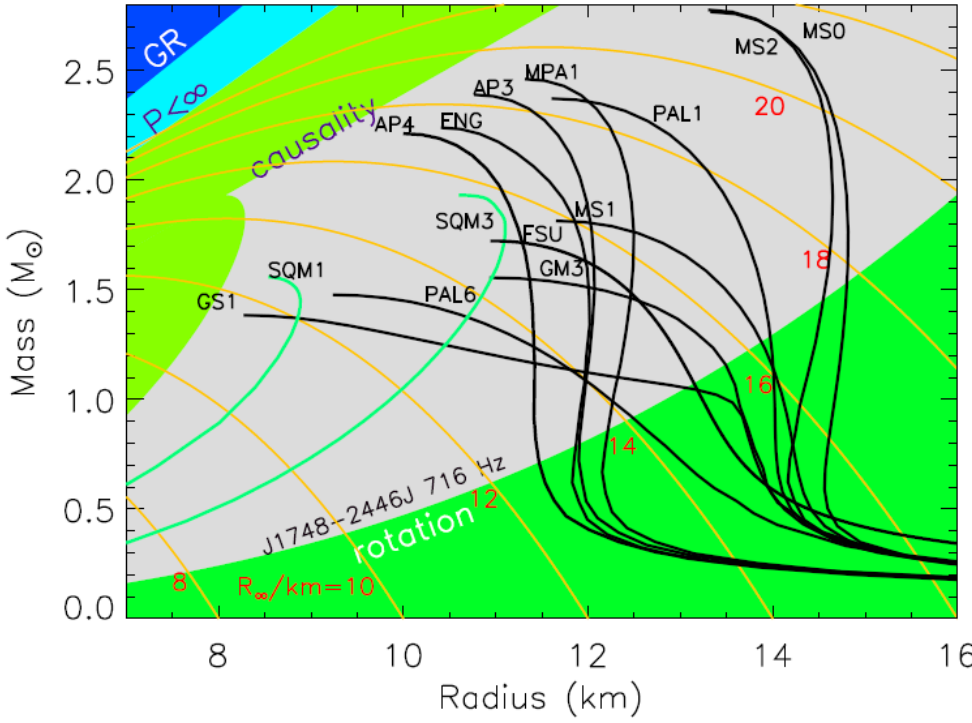


Maximum neutron star mass

J.M. Lattimer

Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 485-515 (2012)





Quark/hybrid stars

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]

The scenario of two families of compact stars

1. Equations of state, mass-radius relations and binary systems

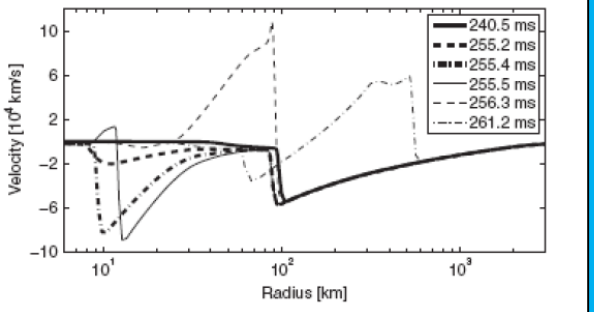
Alessandro Drago[1], Andrea Lavagno[2], Giuseppe Pagliara[1], and Daniele Pigato[2]

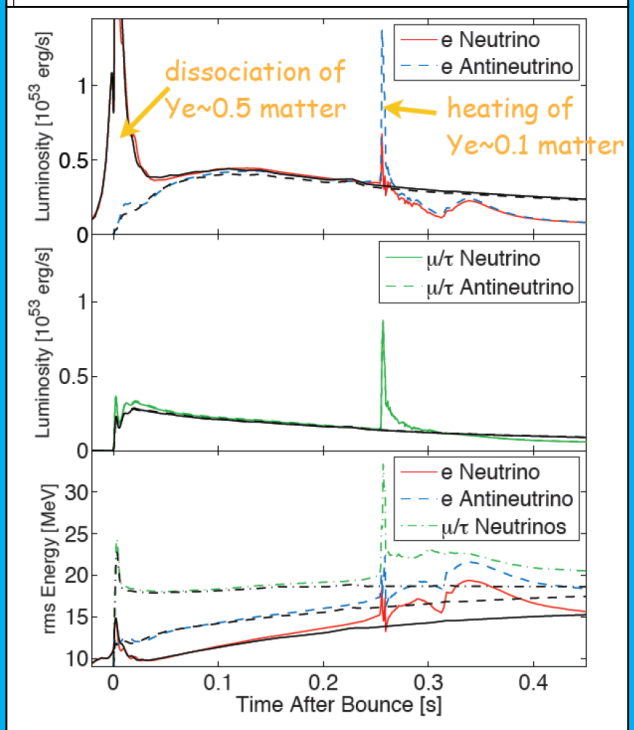
The scenario of two families of compact stars

2. Transition from hadronic to quark matter and explosive phenomena

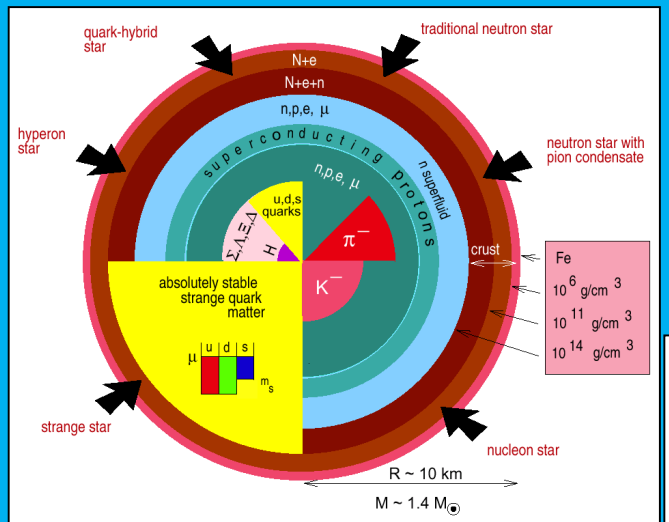
Alessandro Drago and Giuseppe Pagliara

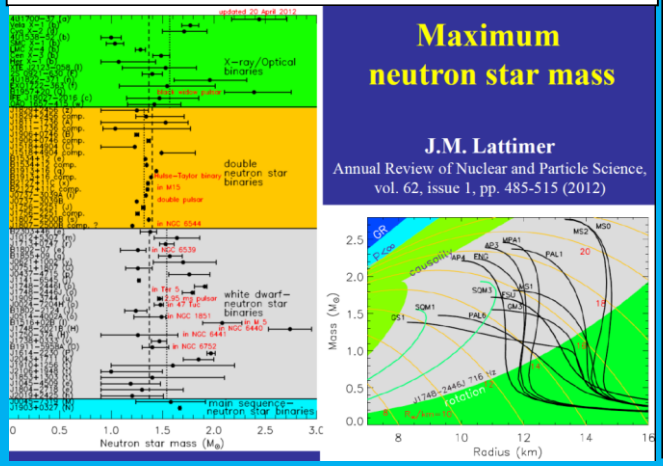
SN-hybrid star connection





Properties of compact stars



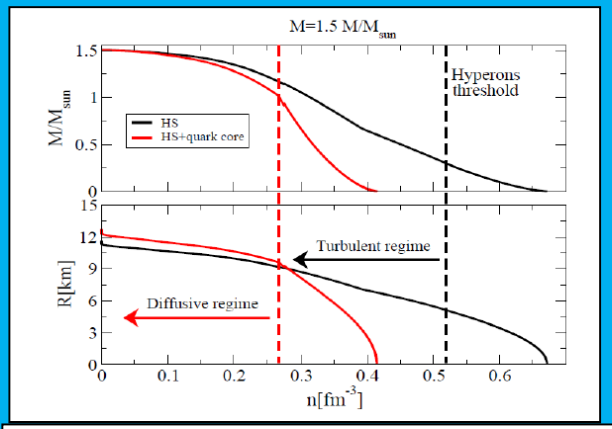


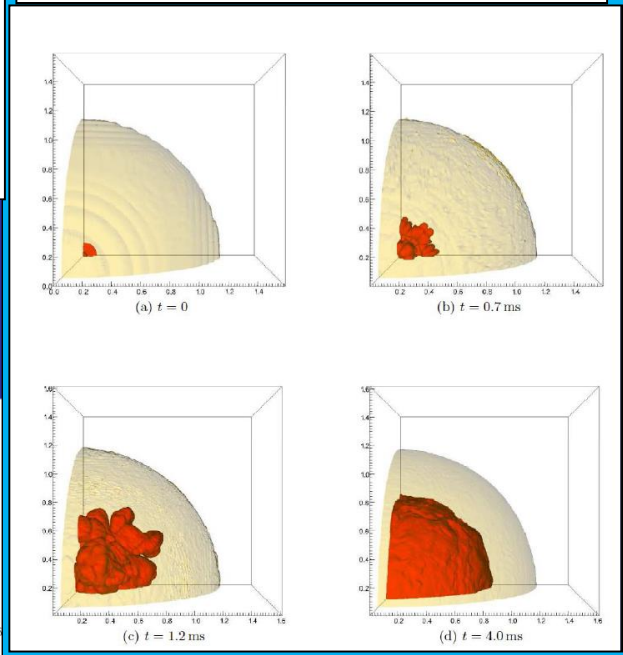
Maximum neutron star mass

J.M. Lattimer

Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 485-515 (2012)

Quark star formation





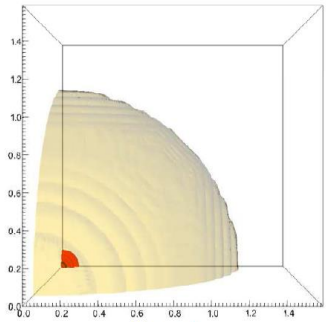
The scenario of two families of compact stars

1. Equations of state, mass-radius relations and binary systems

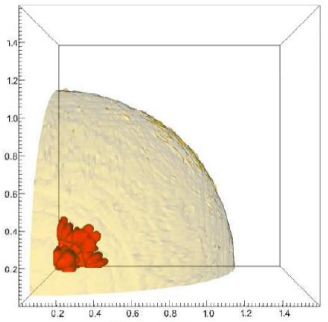
The scenario of two families of compact stars

2. Transition from hadronic to quark matter and explosive phenomena

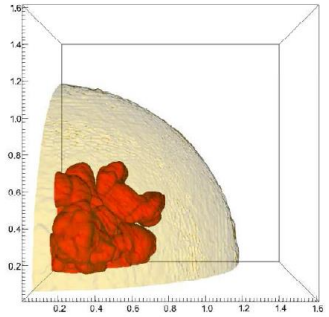
Alessandro Drago and Giuseppe Pagliara



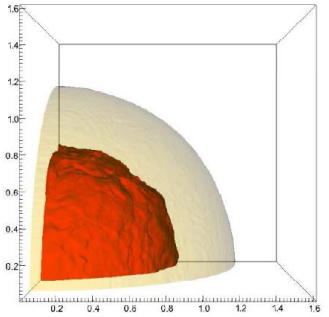
(a) $t = 0$



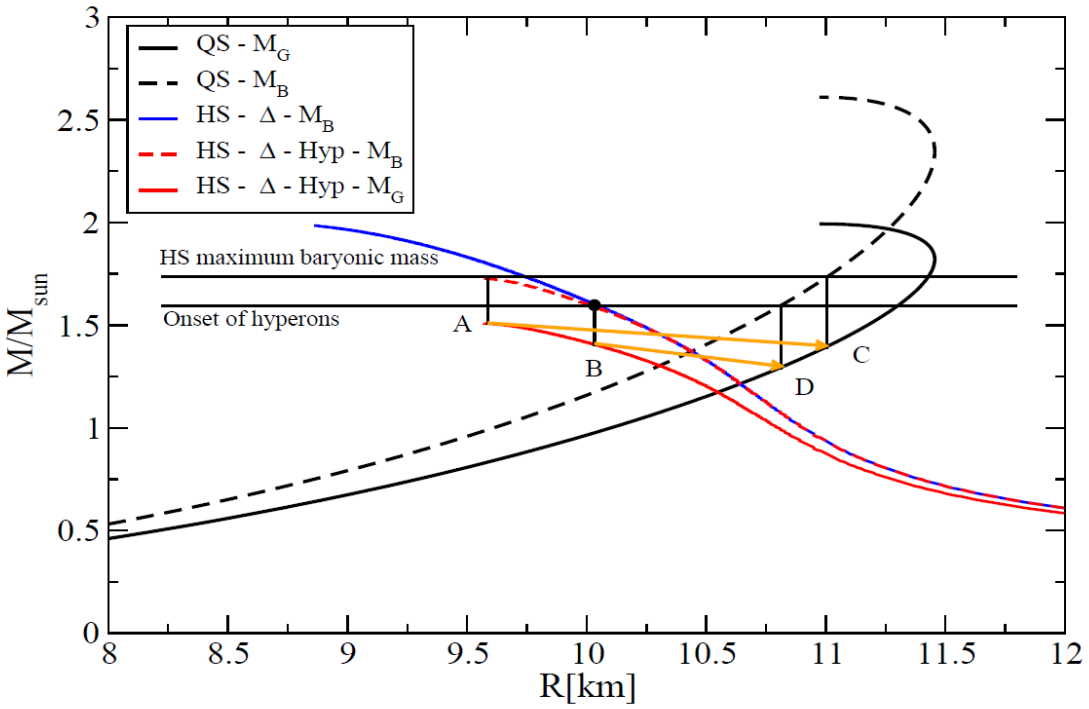
(b) $t = 0.7\,\mathrm{ms}$



(c) $t = 1.2\,\mathrm{ms}$



(d) $t = 4.0\,\mathrm{ms}$



Quark/hybrid stars

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]

The scenario of two families of compact stars

1. Equations of state, mass-radius relations and binary systems

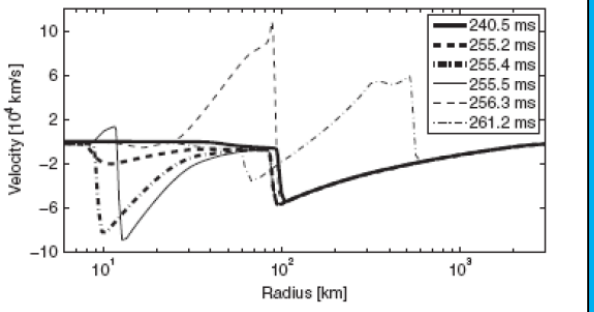
Alessandro Drago[1], Andrea Lavagno[2], Giuseppe Pagliara[1], and Daniele Pigato[2]

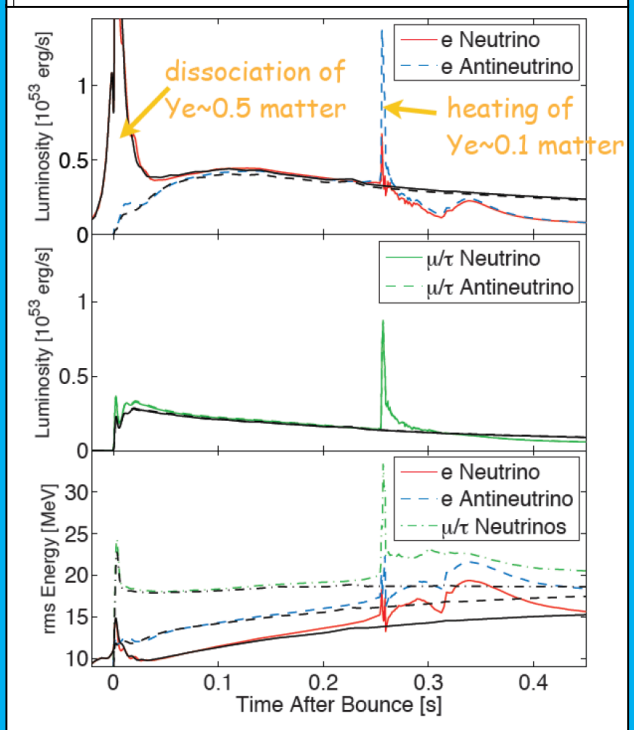
The scenario of two families of compact stars

2. Transition from hadronic to quark matter and explosive phenomena

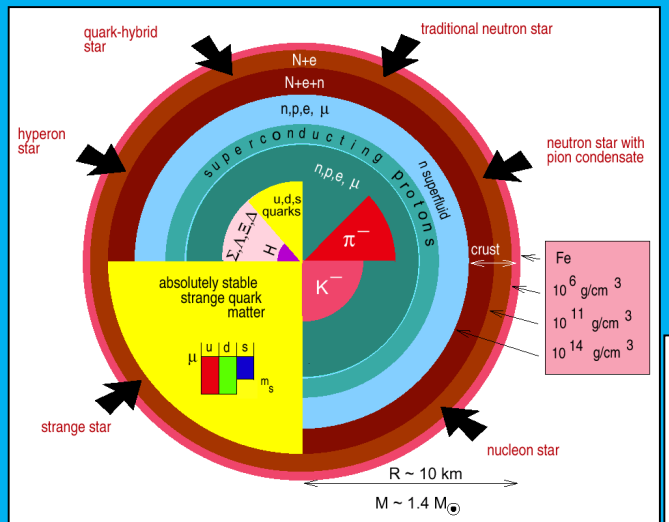
Alessandro Drago and Giuseppe Pagliara

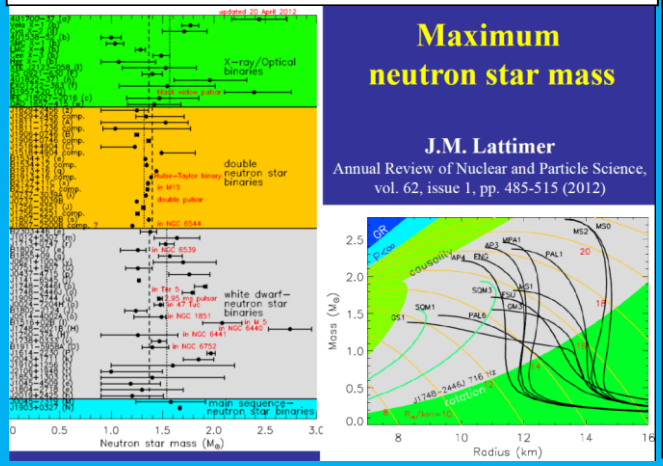
SN-hybrid star connection





Properties of compact stars



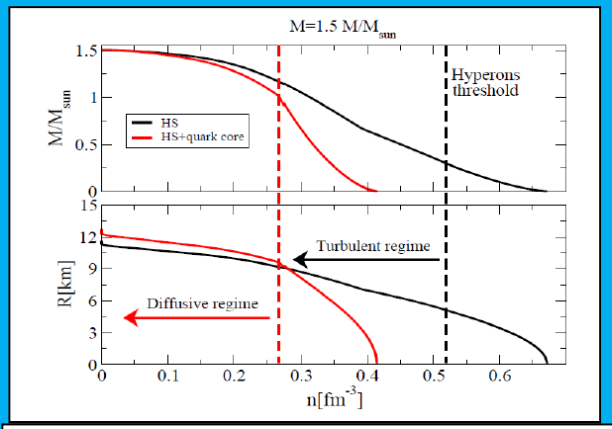


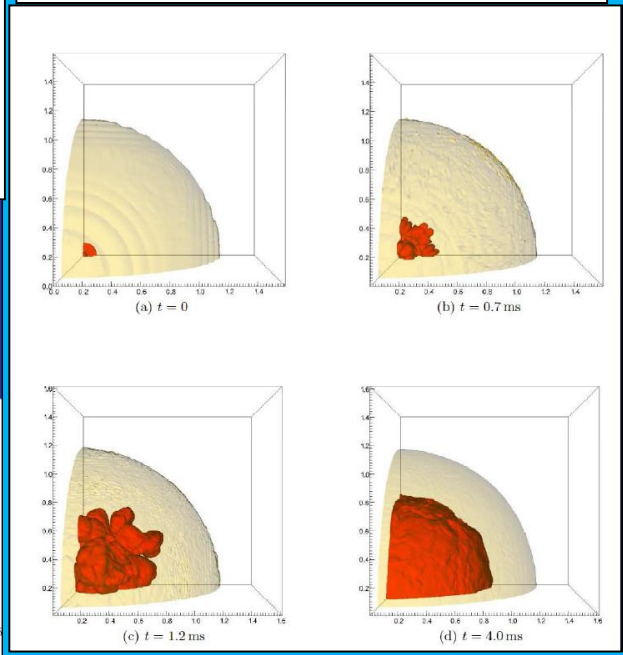
Maximum neutron star mass

J.M. Lattimer

Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 485-515 (2012)

Quark star formation

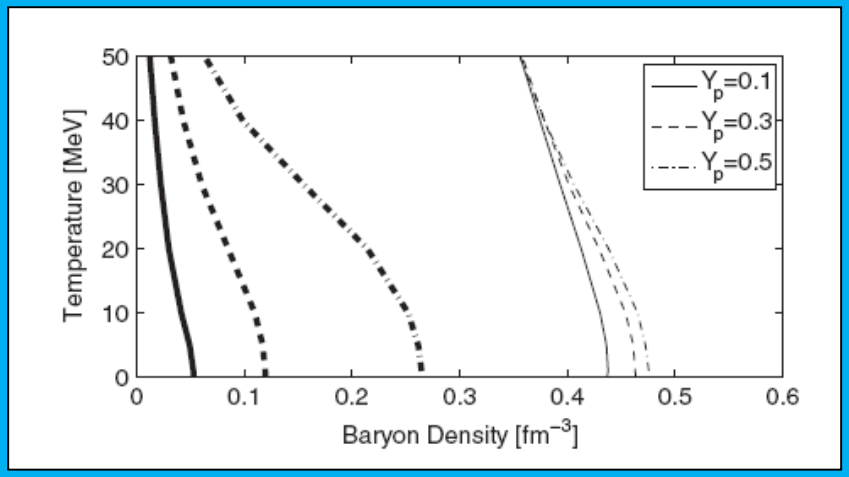


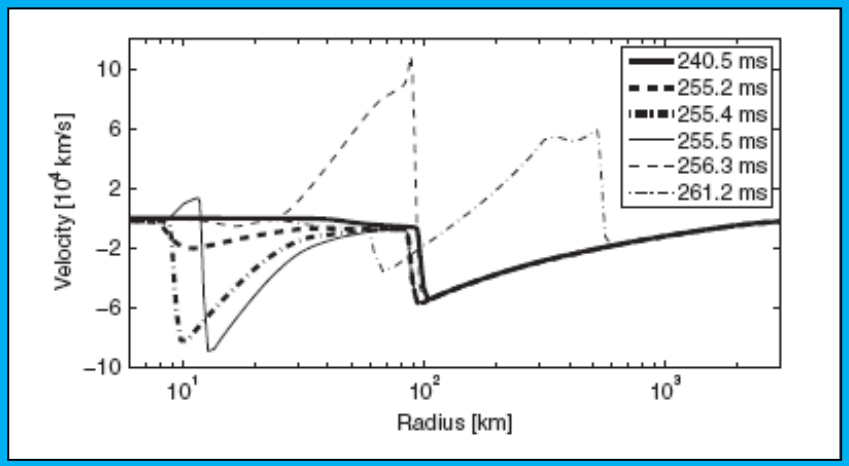


PRL 102, 081101 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

Signals of the QCD Phase Transition in Core-Collapse Supernovae

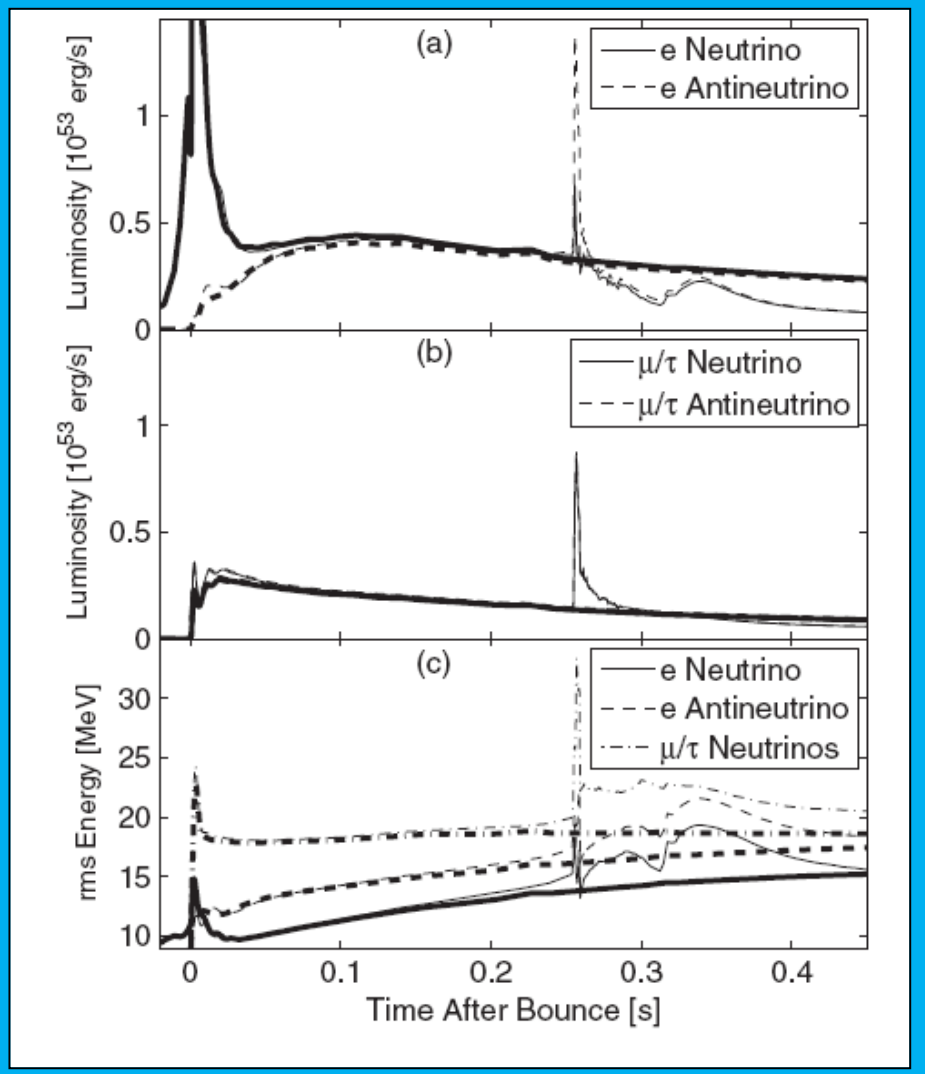
I. Sagert,[1] T. Fischer,[3] M. Hempel,[1] G. Pagliara,[2] J. Schaffner-Bielich,[2] A. Mezzacappa,[4] F.-K. Thielemann,[3] and M. Liebendörfer[3]





Prog. [$M_\odot$]	EOS	t_{pb} [ms]	M_Q [$M_\odot$]	M_{mix} [$M_\odot$]	M_{pns} [$M_\odot$]	E_{expl} [10^{51}erg]	BE [10^{53}erg]	M_G [$M_\odot$]
10	*eos*1	255	0.850	0.508	1.440	0.44	3.40	1.25
10	*eos*2	448	1.198	0.161	1.478	1.64	3.19	1.30
15	*eos*1	209	1.146	0.320	1.608	0.42	4.08	1.38
15	*eos*2	330[a]	1.496	0.116	1.700	...[b]	4.28	1.46

[a]moment of black hole formation
[b]black hole formation before explosion



Thank you !