Delta isobars in neutron stars

(based on 1407.2843 & Phys.Rev. D 89, 043014)

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COMPACT STARS IN THE QCD PHASE DIAGRAM IV, Prerow, 26-30/09/2014

Outline

-) Connection between symmetry energy and thresholds of delta isobars

-) Parameters estimates, equation of state and maximum masses of hadronic stars

-) Radii mesurements: existence of stars with R <10km? (large uncertainties). Tension with mass measurements

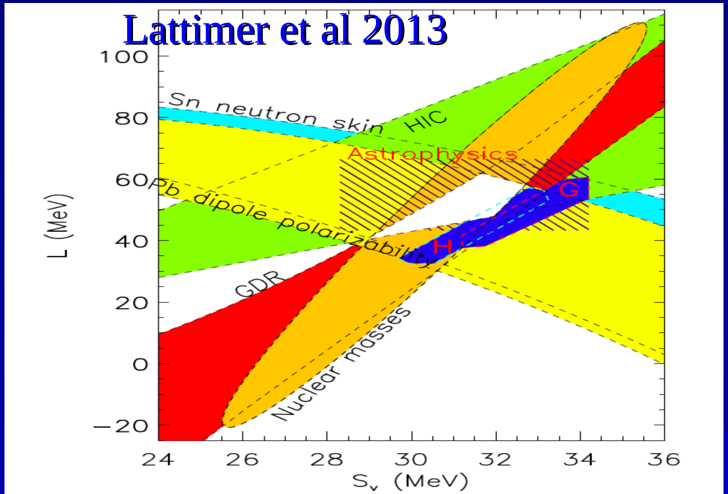
-) Burning of neutron stars, scenario of two families of compact stars

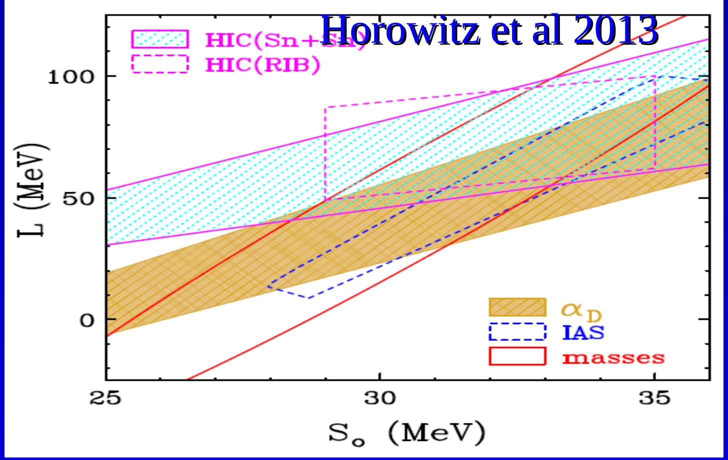
Symmetry energy: the L parameter

Symmetry energy and its density derivative

$$e(n,x) = e(n,1/2) + S_2(n)(1-2x)^2 + \ldots$$

$$S_v = S_2(n_s),$$
$$L = 3n_s(dS_2/dn)_{n_s}$$





Within the old Glendenning mean field parametrizations it was not possible to include this parameter as an additional constraint on nuclear matter

NEUTRON STARS ARE GIANT HYPERNUCLEI?[1]

NORMAN K. GLENDENNING
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Received 1984 March 28; accepted 1984 December 3

$$\mathscr{L} = \sum_B \bar{B}(i\gamma_\mu \partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu)B$$
$$- g_\rho \rho_{\mu 3} J_3{}^\mu + \mathscr{L}_\sigma{}^0 + \mathscr{L}_\omega{}^0 + \mathscr{L}_\rho{}^0 + \mathscr{L}_\pi{}^0 - U(\sigma)$$

$$U(\sigma) = [bm_N + c(g_\sigma \sigma)](g_\sigma \sigma)^3$$

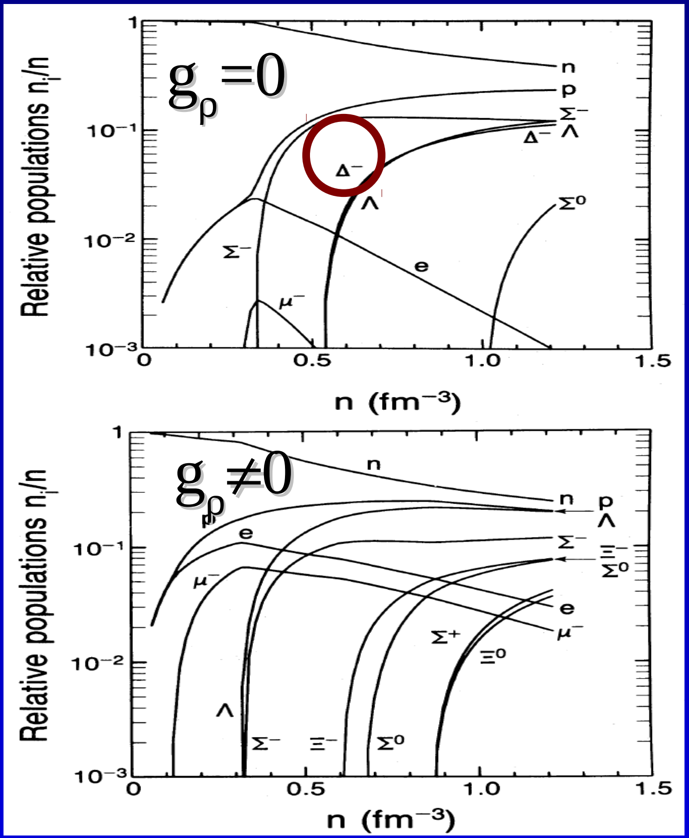
Only S_v could be fixed through g_ρ

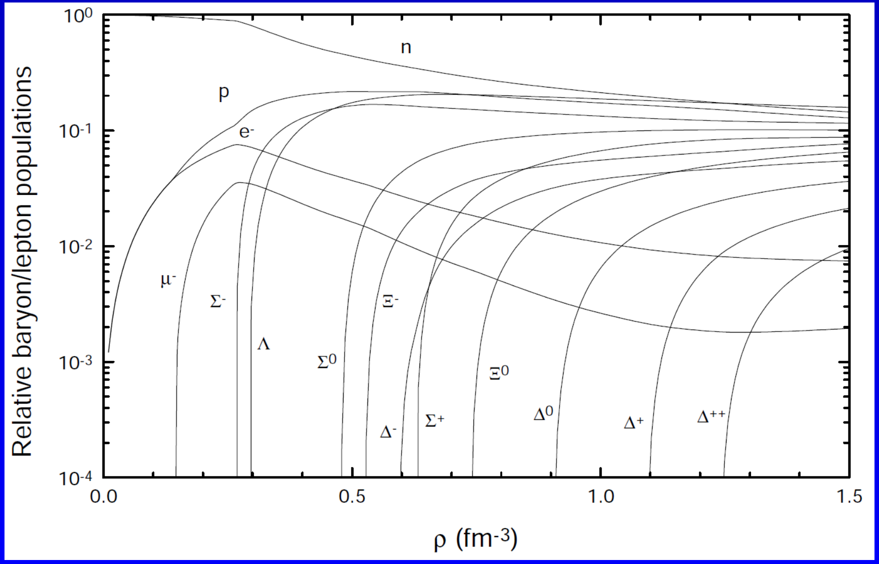
… it turns out that in the GM1-2-3 parametrizations L ~ 80 MeV thus higher than the values indicated by the recent analysis of Lattimer & Lim.

Baryons thresholds equation:

$$\mu_n - q_B\,\mu_e \geq g_{\omega B}\,\omega_0 + g_{\rho B}\,\rho_{03}\,I_{3B} + m_B - g_{\sigma B}\,\sigma$$

Disfavours the appearance of particles, such as Δ^- , with negative isospin charge. Δ^- could form in beta-stable matter only if g_ρ is set =0 (Glendenning 1984).



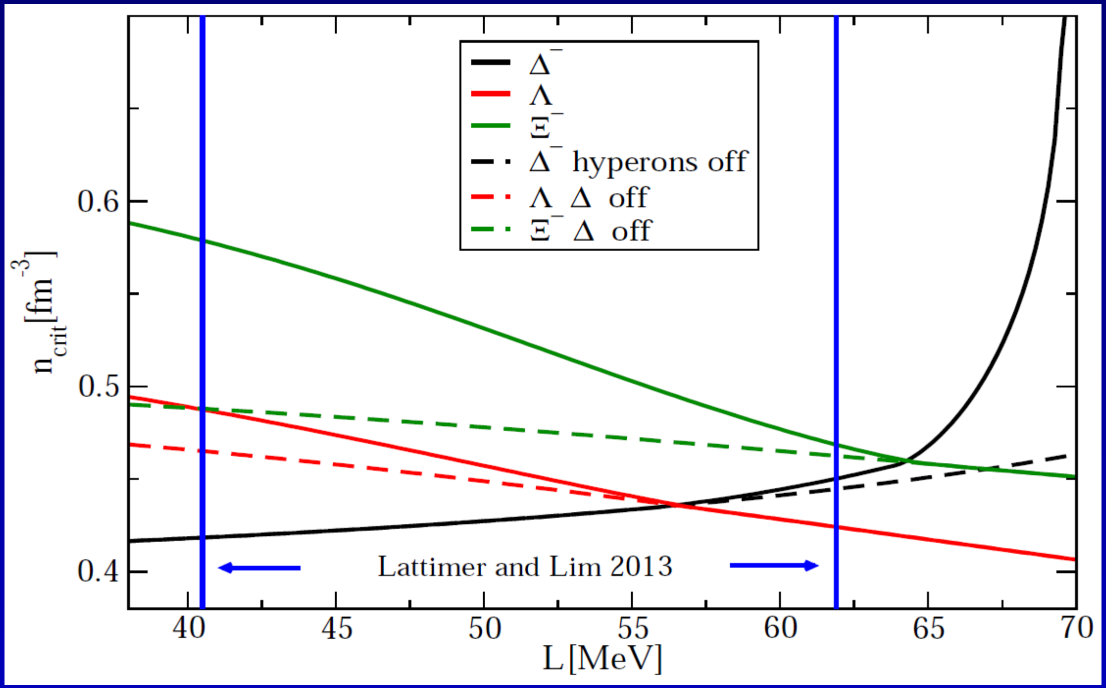


Δ^- easier to form in RHF calculations (see Huber et al 1998) due to the smaller value of g_ρ

A toy model: introduce a density dependence of g_ρ within the GM3 model (density dependence as in Typel et al 2009)

$$f_i(x) = \exp[-a_i(x-1)]$$

The additional parameter "a" allow to fix L. Coupling ratios =1 for Δ, for hyperons potential depths and flavor symmetry (Schaffner 2000).



Glendenning's results

Different behaviour of the hyperons and Δ thresholds as functions of L:

$$g_{\rho n}\rho + \sqrt{k_{Fn}^2 + m_n^{*\,2}} + \mu_e = m_{\Delta^-}^*$$

Punch line: for the range of L indicated by Lattimer & Lim, Δ appear already at 2-3 saturation density, thus comparable to the density of appearance of hyperons. If Δ form before hyperons, hyperons are shifted to higher densities (w.r.t. the case of no Δ)

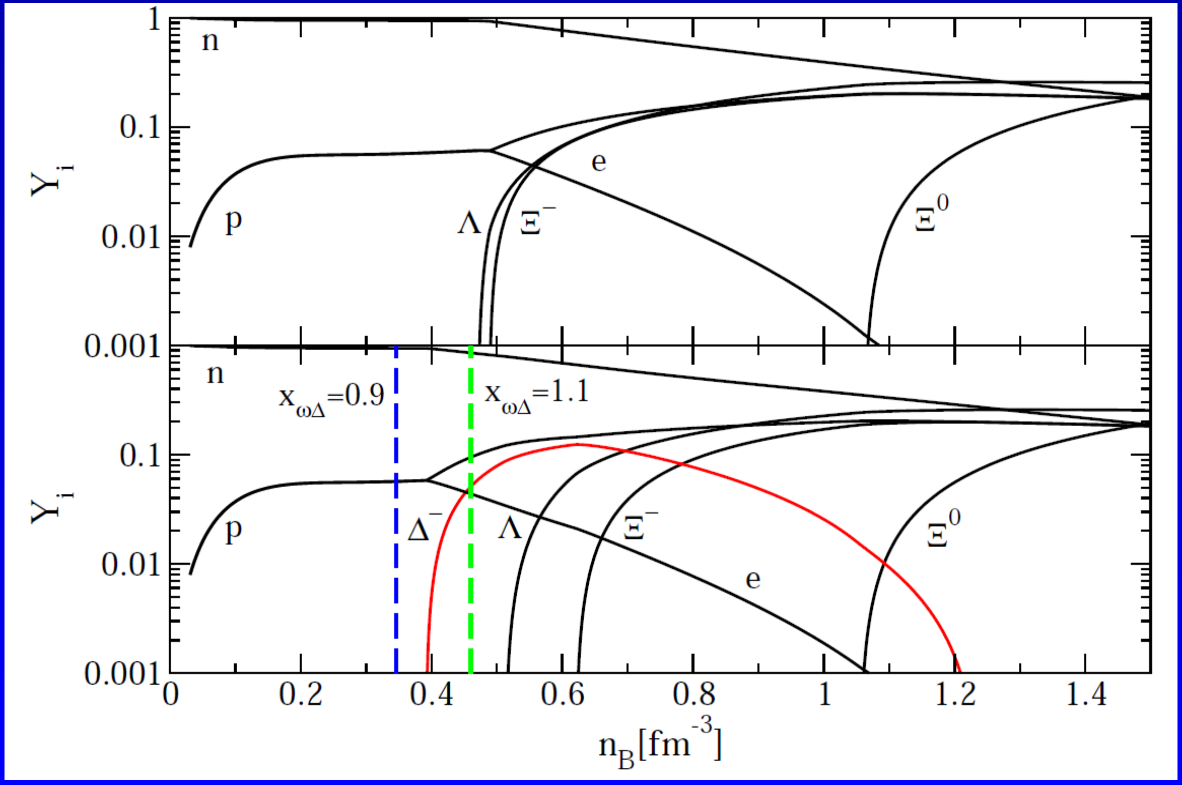
The recent SFHo model (Steiner et al 2013): additional terms added to better exploit the experimental information

$$\begin{aligned}\mathcal{L} \;=\; & \bar{\Psi}\left[i\partial\!\!\!/ - g_\omega \omega\!\!\!/ - \tfrac{1}{2} g_\rho \vec{\rho}\!\!\!/ \cdot \vec{\tau} - M + g_\sigma \sigma - \tfrac{1}{2} e\left(1+\tau_3\right) A\!\!\!/\right]\Psi + \tfrac{1}{2}\left(\partial_\mu \sigma\right)^2 \\ & - V(\sigma) - \tfrac{1}{4} f_{\mu\nu} f^{\mu\nu} + \tfrac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \tfrac{1}{4} \vec{B}_{\mu\nu} \cdot \vec{B}^{\mu\nu} + \tfrac{1}{2} m_\rho^2 \vec{\rho}^\mu \cdot \vec{\rho}_\mu - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + \frac{\zeta}{24} g_\omega^4 \left(\omega^\mu \omega_\mu\right)^2 + \frac{\xi}{24} g_\rho^4 \left(\vec{\rho}^\mu \cdot \vec{\rho}_\mu\right)^2 + g_\rho^2 f\left(\sigma, \omega_\mu \omega^\mu\right) \vec{\rho}^\mu \cdot \vec{\rho}_\mu ,\end{aligned}$$

Steiner et al 2005

PROPERTIES AT SATURATION DENSITY AND NEUTRON STAR PROPERTIES FOR THE THE DIFFERENT EOSS UNDER INVESTIGATION. THE DEFINITION OF ALL THE QUANTITIES IS GIVEN IN THE TEXT.

EOS	n_B^0 [fm^{-3}]	E_0 [MeV]	K [MeV]	K' [MeV]	J [MeV]	L [MeV]	m_n^*/m_n -	m_p^*/m_p -	$R_{1.4}$ [km]	$M_{T=0,Max}$ [$M_\odot$]	$M_{s=4,Max}$ [$M_\odot$]
SFHo	0.1583	16.19	245.4	-467.8	31.57	47.10	0.7609	0.7606	11.88	2.059	2.27
SFHx	0.1602	16.16	238.8	-457.2	28.67	23.18	0.7179	0.7174	11.97	2.130	2.36
STOS(TM1)	0.1452	16.26	281.2	-285.3	36.89	110.79	0.6344	0.6344	14.56	2.23	2.62
HS(TM1)	0.1455	16.31	281.6	-286.5	36.95	110.99	0.6343	0.6338	13.84	2.21	2.59
HS(TMA)	0.1472	16.03	318.2	-572.2	30.66	90.14	0.6352	0.6347	14.44	2.02	2.48
HS(FSUgold)	0.1482	16.27	229.5	-523.9	32.56	60.43	0.6107	0.6102	12.52	1.74	2.34
LS(180)	0.1550	16.00	180.0	-450.7	28.61	73.82	1	1	12.16	1.84	2.02
LS(220)	0.1550	16.00	220.0	-411.2	28.61	73.82	1	1	12.62	2.06	2.14



Introducing both hyperons and Δ in the SFHo model: Δ appear before hyperons even in the case of $x_{\omega\Delta} > 1$.

Do we have any experimental/theoretical information on $x_{\omega\Delta}$ & $x_{\sigma\Delta}$?

Electron, pion scattering photoabsorption on nuclei (O'Connel et al 1990, Wehrberger et al1989...). Indications of a Δ potential in the nuclear medium deeper than the nucleon potential. Several phenomenological and theoretical analyses lead to similar conclusions.

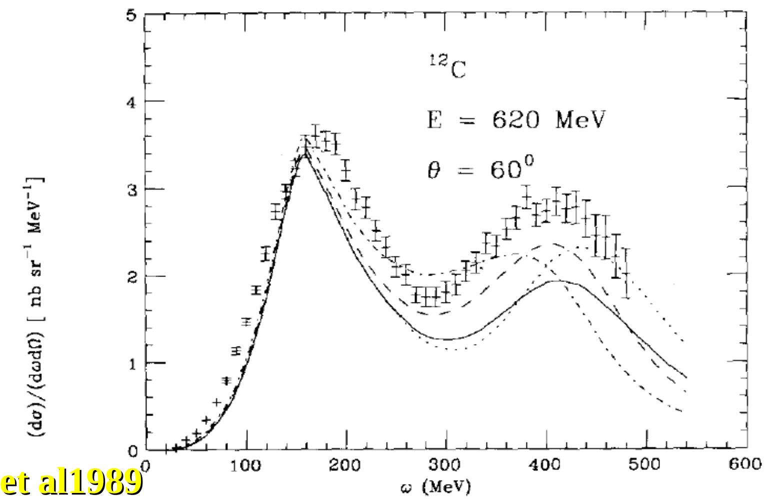


Fig. 13. Cross section for electron scattering on ^{12}C at incident electron energy $E = 620$ MeV and scattering angle $\theta = 60°$ as a function of energy transfer ω for standard nucleon and different Δ-couplings. The lines are the results for the sum of the contribution from nucleon knockout and Δ-excitation. The dotted line shows the cross section for free Δ's, and the dashed and dot-dashed lines for no coupling to the vector field and a ratio $r_s = 0.15$ and 0.30 of the scalar coupling of the Δ to the scalar coupling of the nucleon. The solid line is obtained for universal coupling. The data are from ref. [16]).

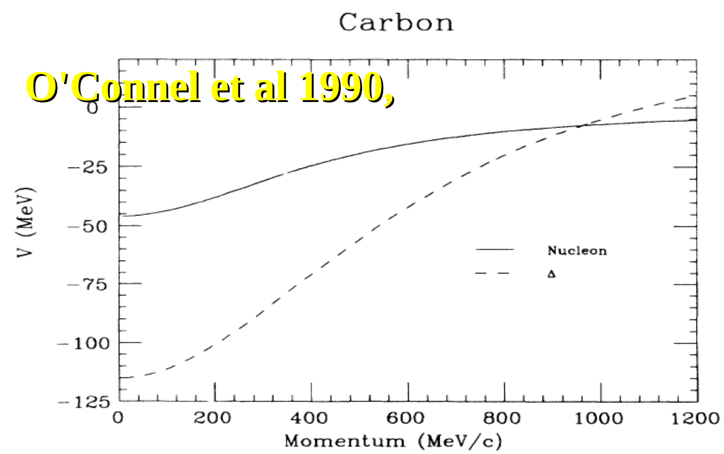


FIG. 4. Phenomenological nucleon-nucleus, solid line, and Δ nucleus, dashed line, momentum-dependent potentials for C.

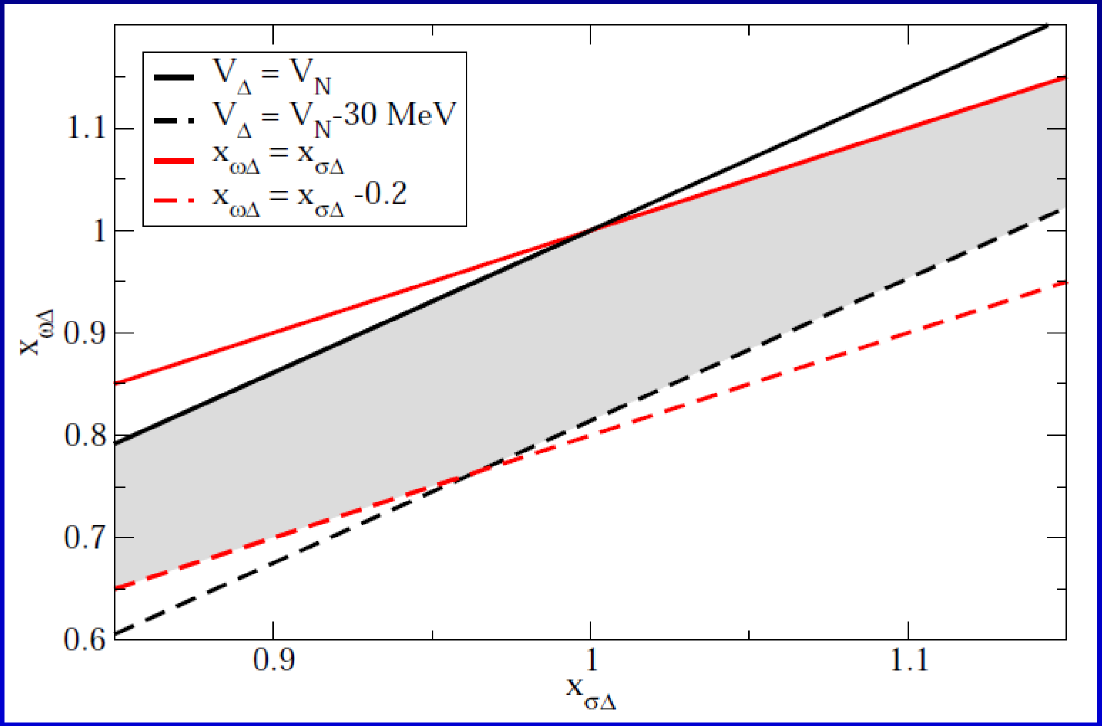
Phenomenological potentials:

$$\omega = E_f - E_i$$

$$= (p_f^2 + W^2)^{1/2} + V_W(p_f) - (p_i^2 + M^2)^{1/2} - V_N(p_i)$$

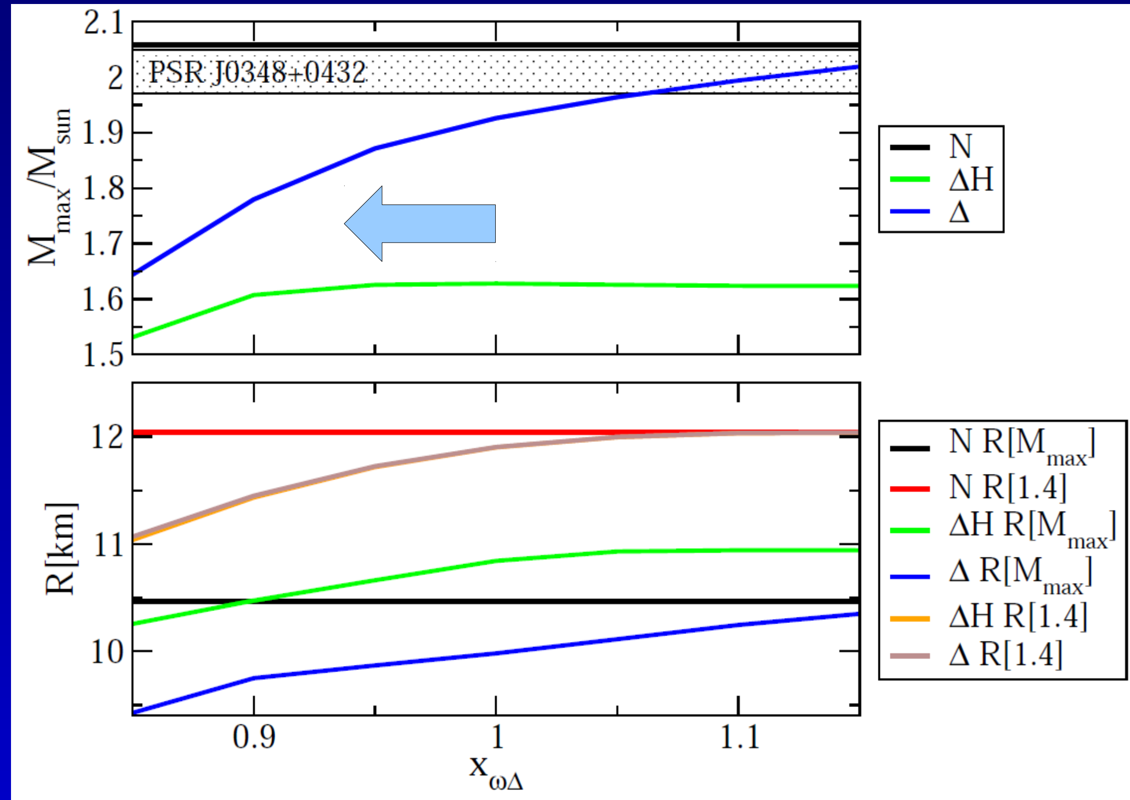
$$V(p) = -V_0/(1 + p^2/p_0^2) + V_1$$

This allows to constrain the free parameters within the RMF model. Notice: coupling with ω mesons suppressed wrt the coupling with the σ meson. The coupling(ratio) with the ρ meson fixed to 1.

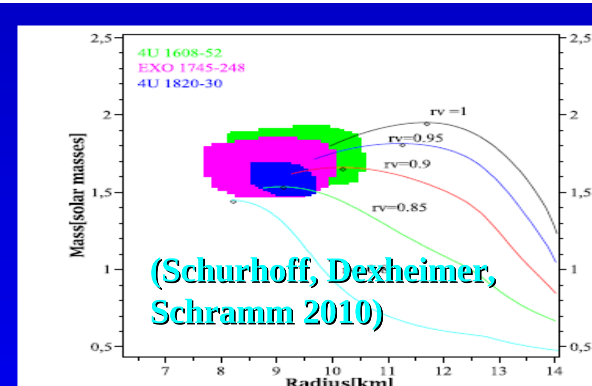


Implications for compact stars ?

Maximum mass and radii: the maximum mass is significantly smaller than the measured ones. Also, very compact stellar configurations are possible.

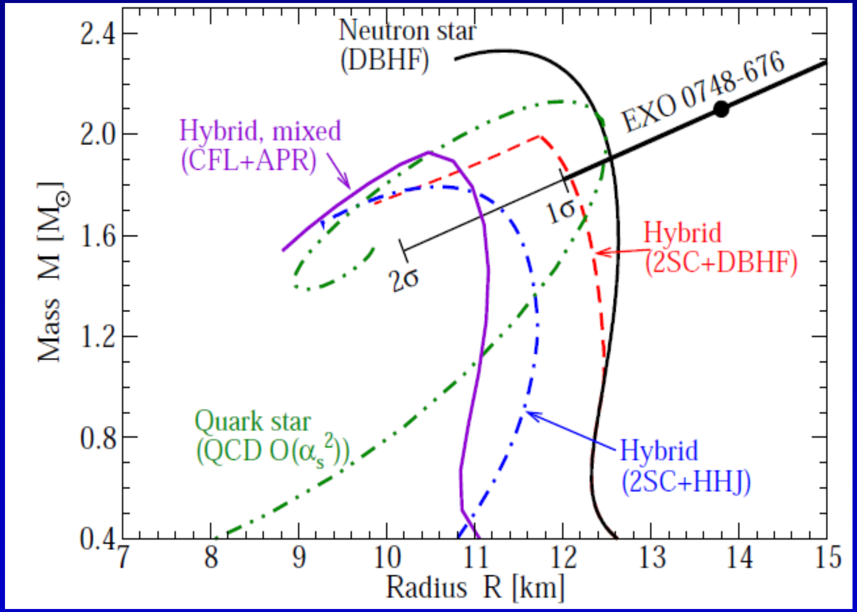


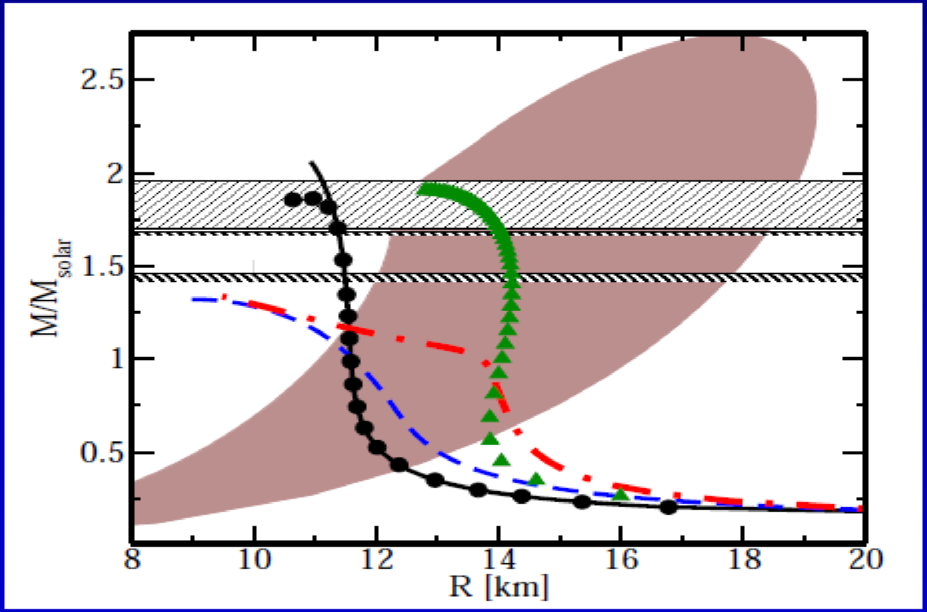
See also:



Punchline/?: beside the "hyperon puzzle" is there also a "delta isobars puzzle"?

Quark matter?





Alford et al Nature 2006

Kurkela et al 2010

pQCD calculations: " … equations of state including quark matter lead to hybrid star masses up to 2Ms, in agreement with current observations. For strange stars, we find maximal masses of 2.75Ms and conclude that confirmed observations of compact stars with M > 2Ms would strongly favor the existence of stable strange quark matter"

Before the discoveries of the two $2M_{sun}$ stars!!

… is this surprising?

Heavy ions physics: (Kolb & Heinz 2003)

Also at finite density the quark matter equation of state should be stiffer than the hadronic equation of state in which new particles are produced as the density increases

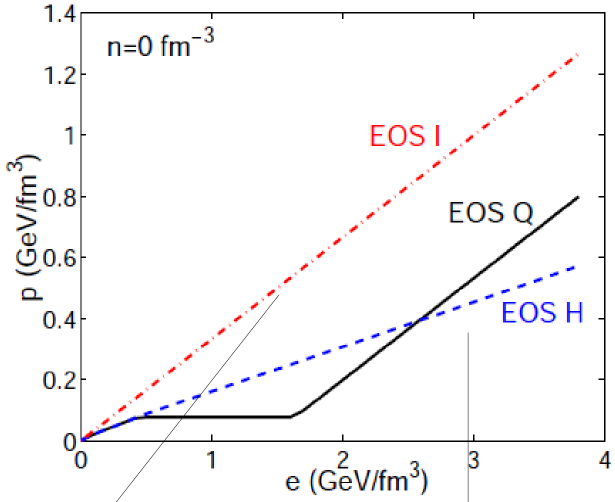
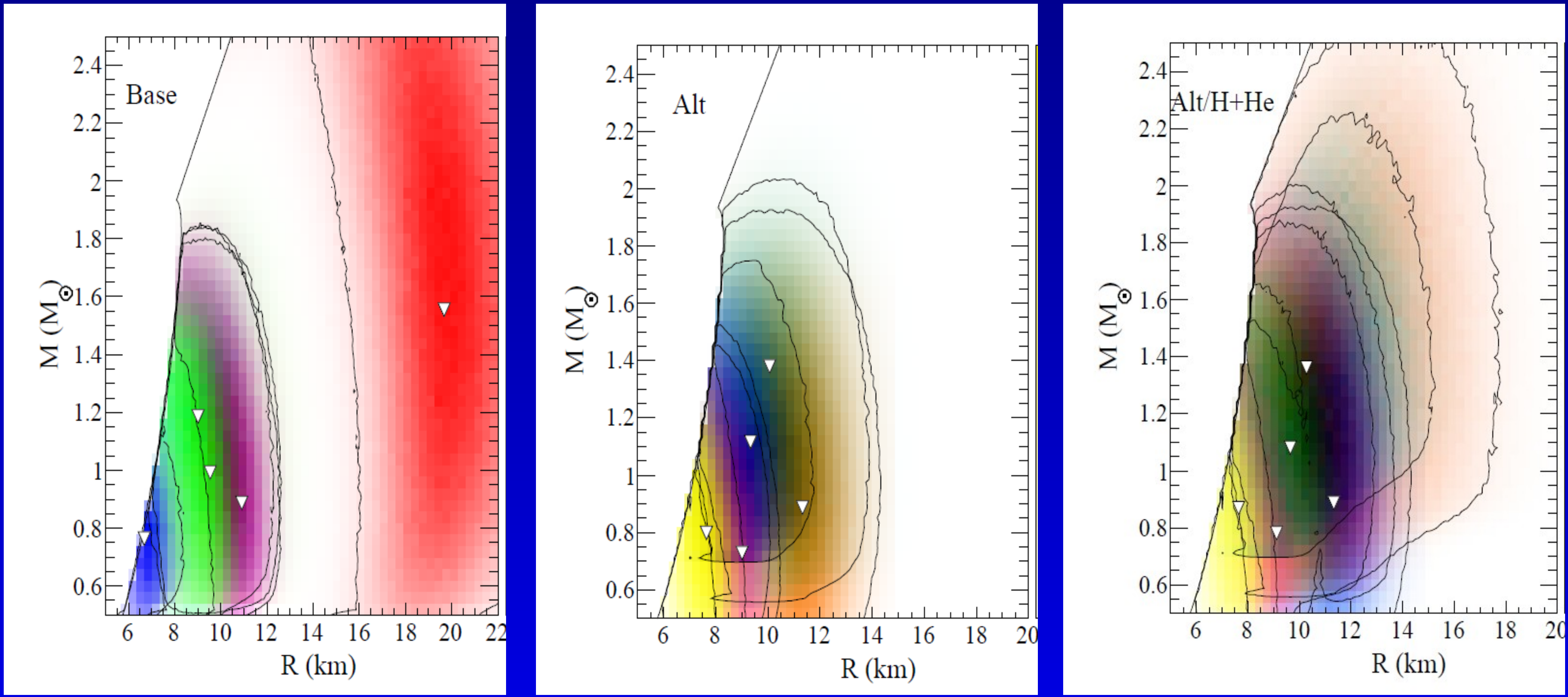


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

p=e/3 massless quarks

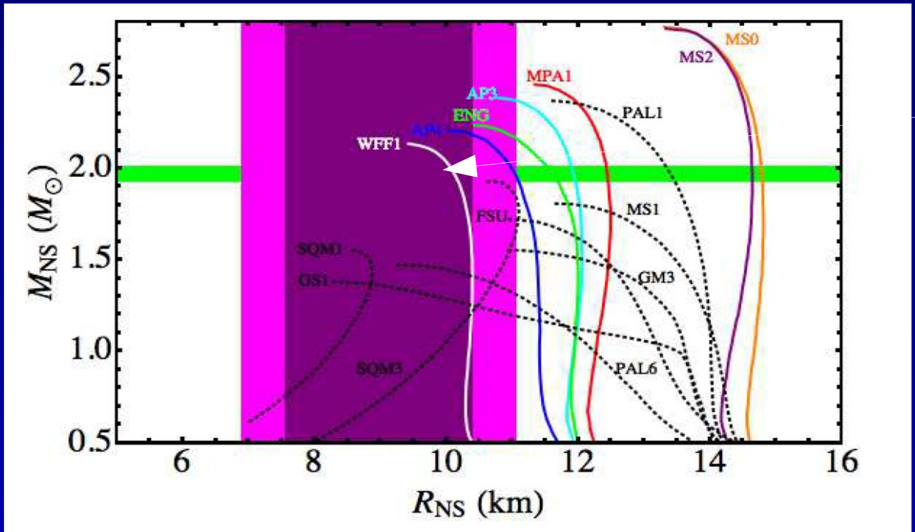
Hadron resonance gas p=e/6

Recent radii measurements

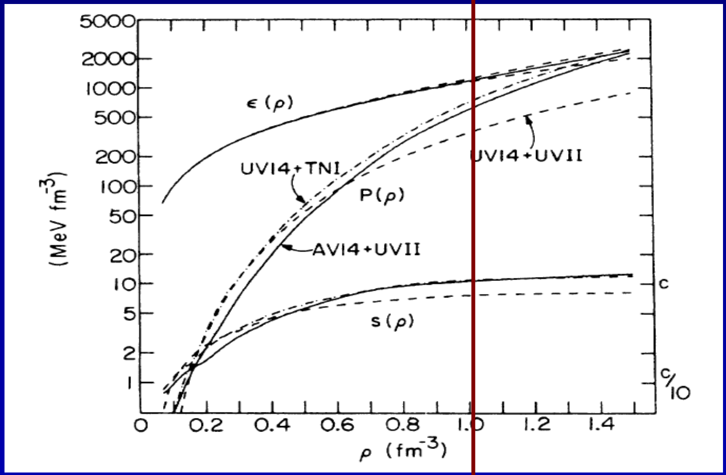


Guillot et al. ApJ772(2013)7

Lattimer and Steiner 1305.3242



Wiringa et al 1988, nice, but:



R=9.1±1.3 km. Updated to 9.4±1.2 (September 2014)

It violates causality

the canonical 1.4 $M_\odot$ neutron star has a central density $\rho_c = 0.57$ fm^{-3} for UV14 plus UVII and 0.66 fm^{-3} for both AV14 plus UVII and UV14 plus TNI, where the

Only nucleons up to very large densities. Similarly for AP4

Tension between different measuremets:

high masses → stiff equation of state

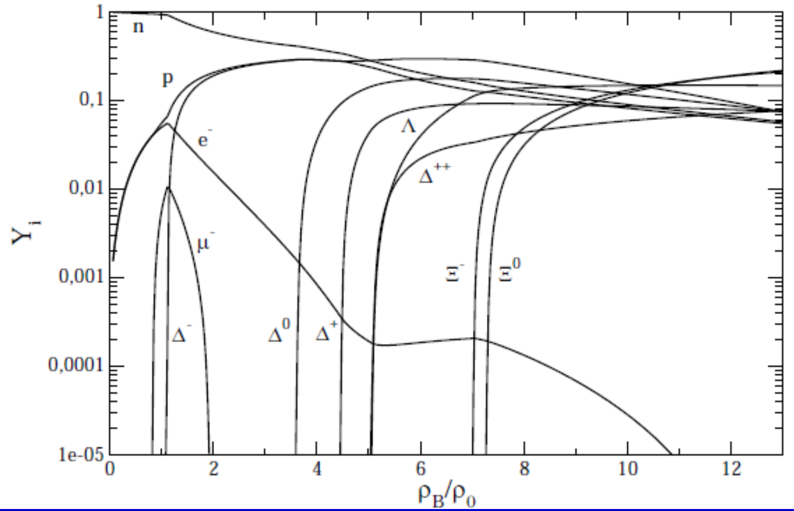
small radii → soft equation of state

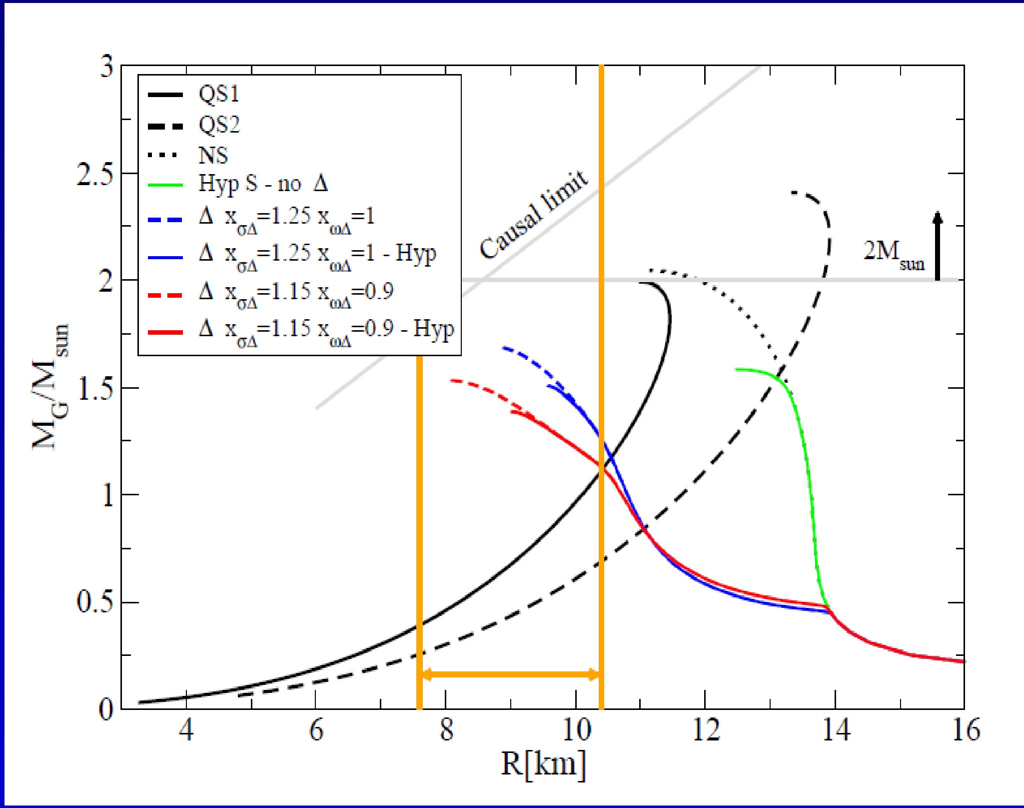
→ large central densities

→ formation of new particles

Drago, Lavagno, G.P. 2013

(results from RMF models for hadronic matter and simple parametrizations for quark matter)





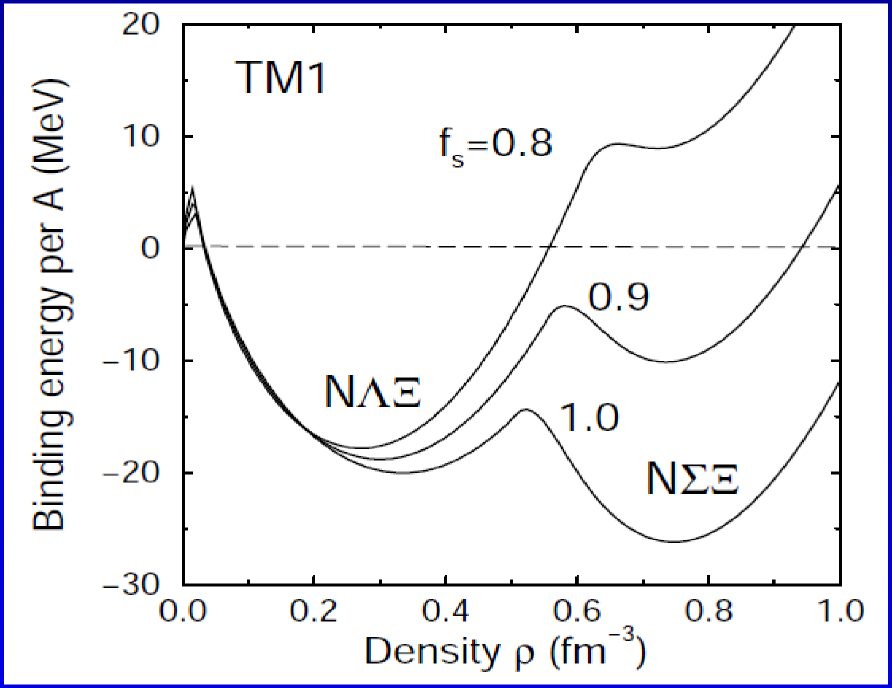
Two families of compact stars:

1) low mass (up to ~1.5 Msun) and small radii (down to 9-10km) stars are hadronic stars (containing nucleons, Δ and hyperons) and they are metastable

2) high mass and large radii stars are strange stars (strange matter is absolutely stable (Bodmer-Witten hyp.))

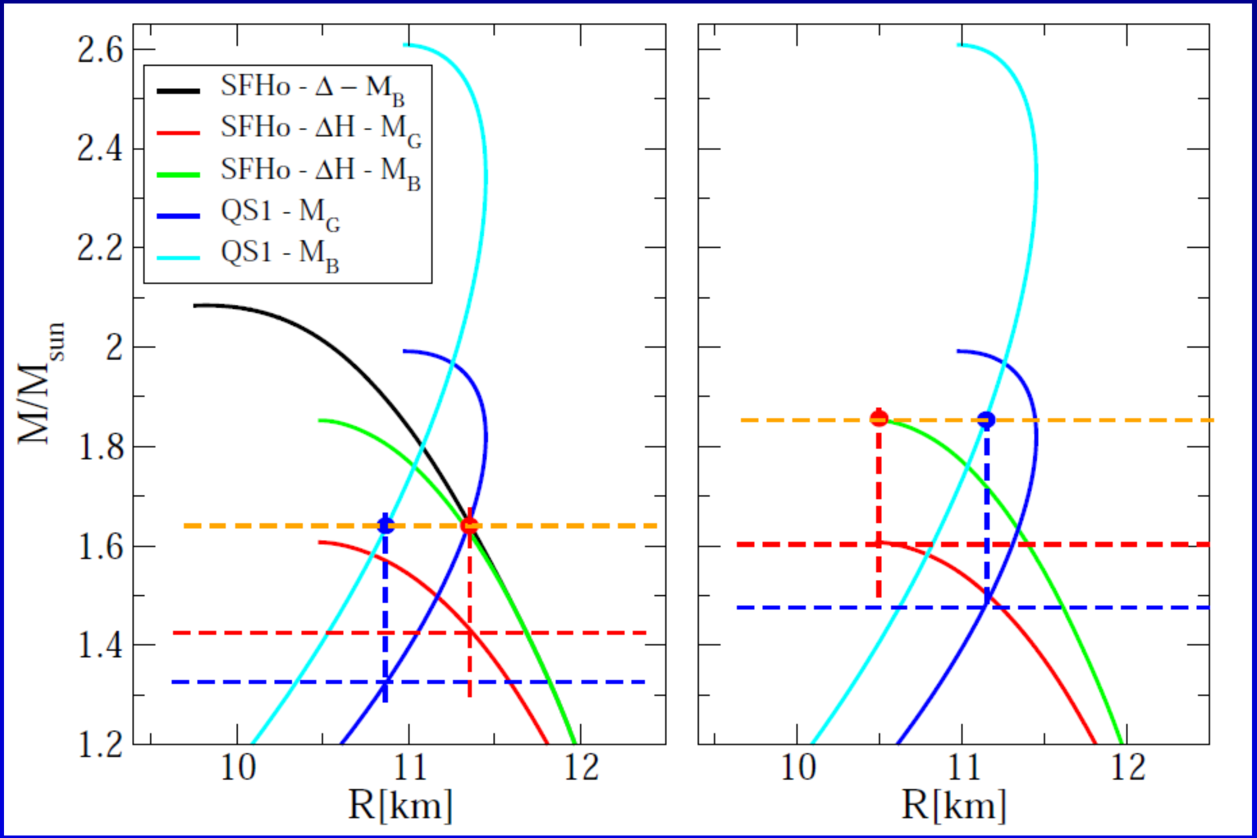
What prevents the conversion of a metastable hadronic star?

A star containing only nucleons and Δ cannot convert into a quark star because of the lack of strangeness (need for multipole simultaneous weak interactions).
Only when hyperons start to form the conversion can take place.



New minima of BE/A could appear when increasing strangeness, (very) strange hypernuclei (Schaffner-Bielich- Gal 2000)

Why conversion should then occur? Quark stars are more bound: at a fixed total baryon number they have a smaller gravitational mass wrt hadronic stars



Hydro simulations

Input from microphysics:

1) EoS of hadronic matter & quark matter at finite temperature: at the moment both beta-stable, lepton number not conserved :-(

2) Detonation or deflagration & laminar burning velocity (from Niebergal et al 2010): at the moment only deflagration has been tested based on the results of Drago et al 2007 where a strong deflagration has been found in all the cases.

Condition for exothermic combustion

$$e_h(P,X) > e_q(P,X)$$

$$X = (e+P)/n_B^2$$

3+1D code developped by Hillebrandt and collaborators for the study of SNIa adapted, by use of an effective relativistic potential, for handling the large compactness of NSs, (see Roepke et al A&A2005) Best resolution 10m.

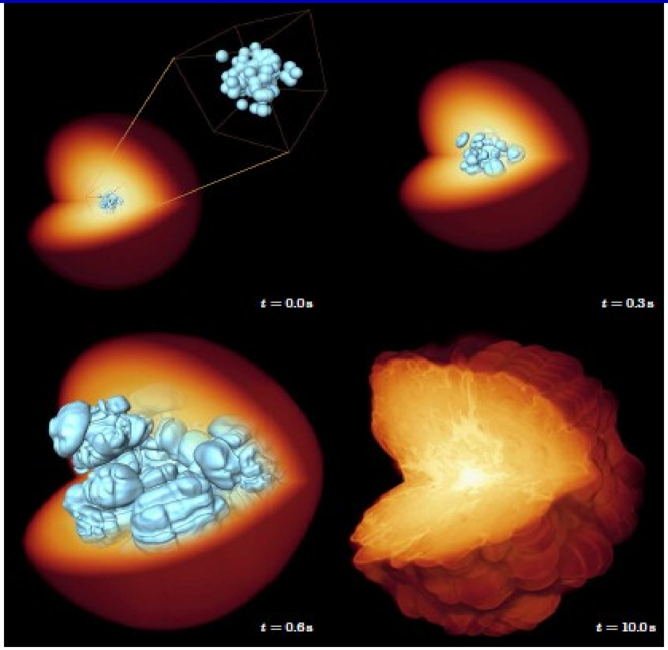


FIGURE 1. Snapshots from a full-star SN Ia simulation starting from a multi-spot ignition scenario. The logarithm of the density is volume rendered indicating the extend of the WD star and the isosurface corresponds to the thermonuclear flame. The last snapshot marks the end of the simulation and is not on scale with the earlier snapshots.

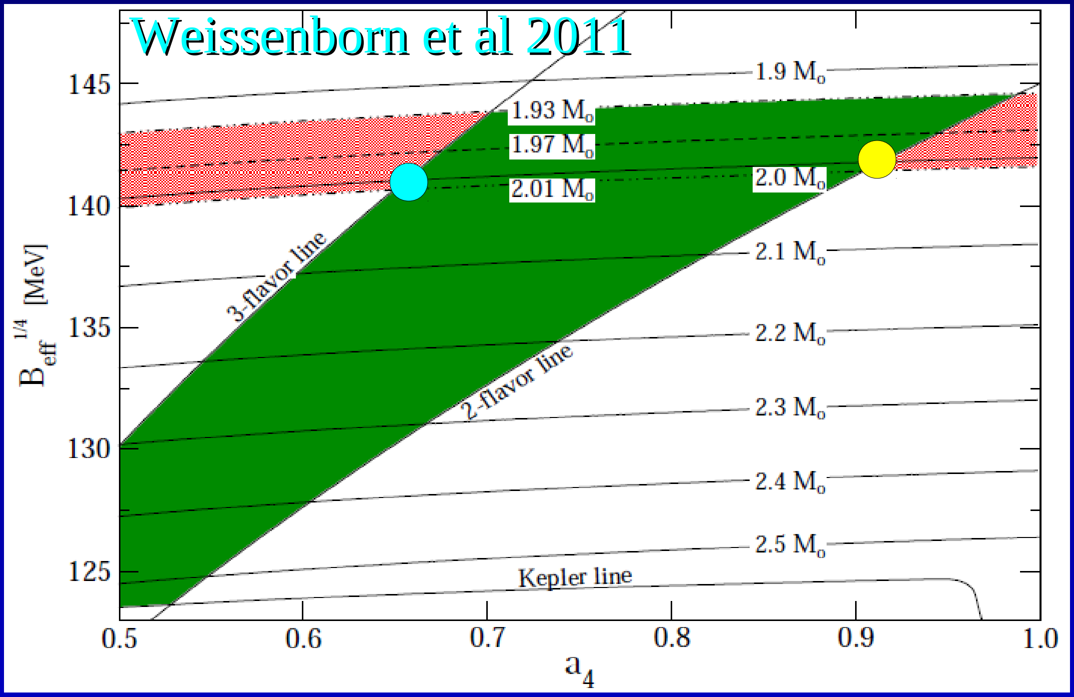
Within a simple parametrization:

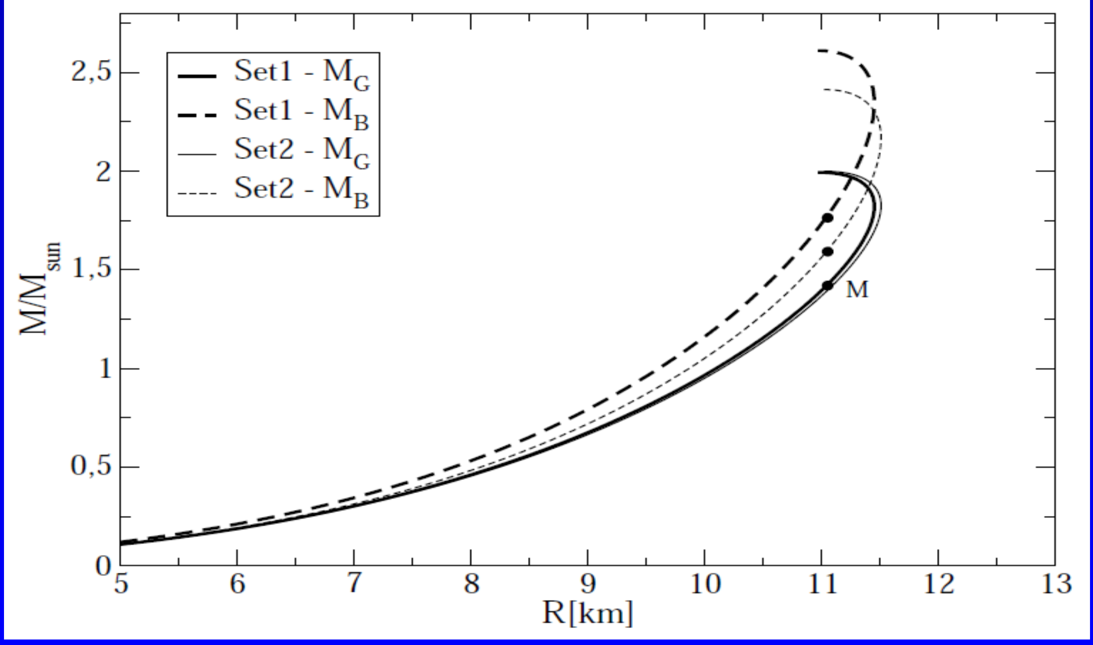
$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1-a_4) + B_{eff}$$

Two EoSs which provide a maximum mass of $2M_{sun}$

- E/A=860 MeV(set1)
- E/A=930 MeV(set2)

Different QSs binding energy M_B-M_G





Conversion of a 1.4 M_{sun} star

-) Rayleigh-Taylor instabilities develop and the conversion occurs on time scales of ms.
-) The burning stops before the whole hadronic matter has converted (the process is no more exothermic, about 0.5 M_{sun} of unburned material)
-) A succesfull conversion need a small E/A, no conversion is possible with set2 (the one with a larger E/A=smaller binding energy)

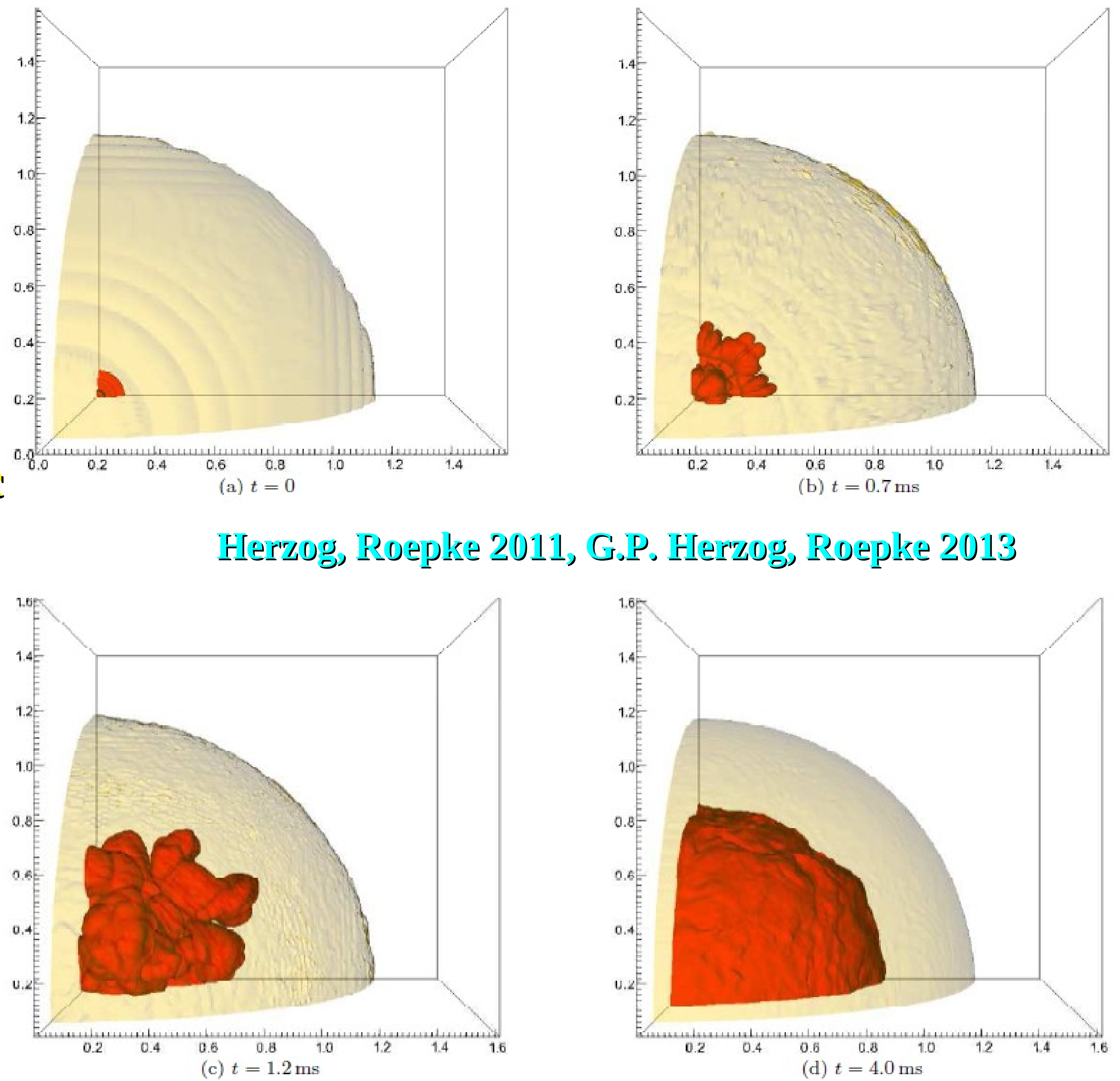


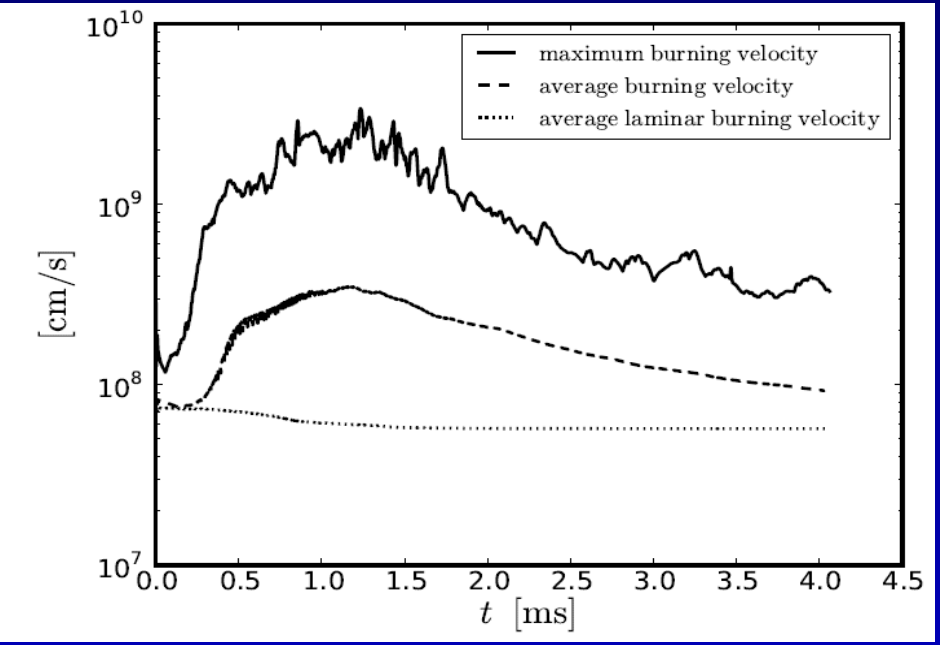
FIG. 1: (color online) Model: Set 1, $M = 1.4 M_\odot$. Conversion front (red) and surface of the neutron star (yellow) at different times t. Spatial units 10^6 cm.

Fractal dimension (Blinnikov et al 2005)

$$D = 2 + D_0\,\gamma^2$$

$$D_0 \sim 0.6$$

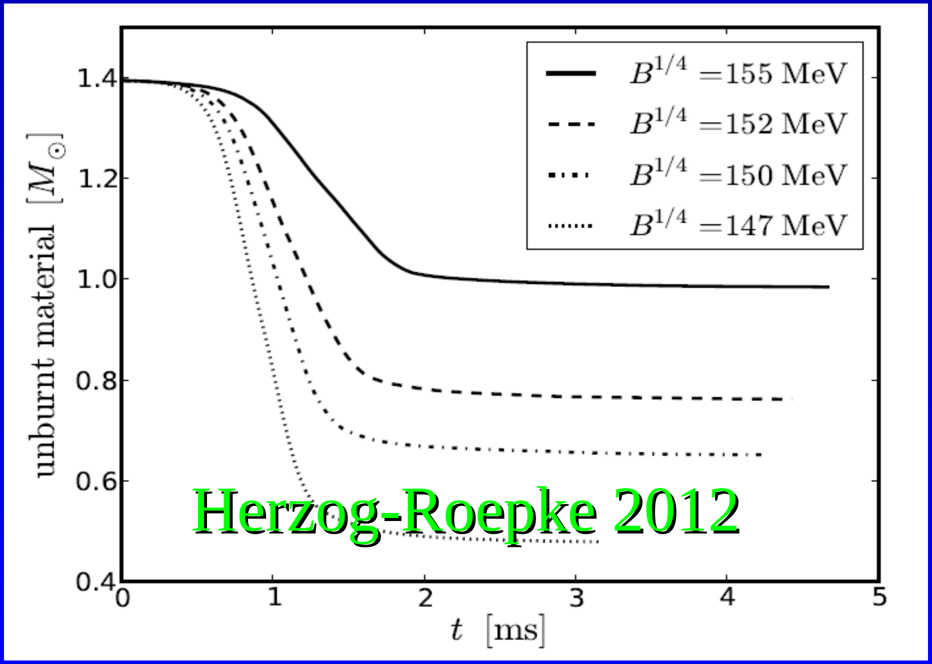
$$\gamma = 1 - e_2/e_1$$



To estimate the final temperature:

$$\Delta\left(\frac{E}{A}\right)(T,\rho_B^h) \equiv \frac{e_h(u_h,\rho_B^h,T_h)}{\rho_B^h(u_h)} - \frac{e_q(u_q,\rho_B^q,T)}{\rho_B^q(u_q)} = c_V^q(T-T_h)$$

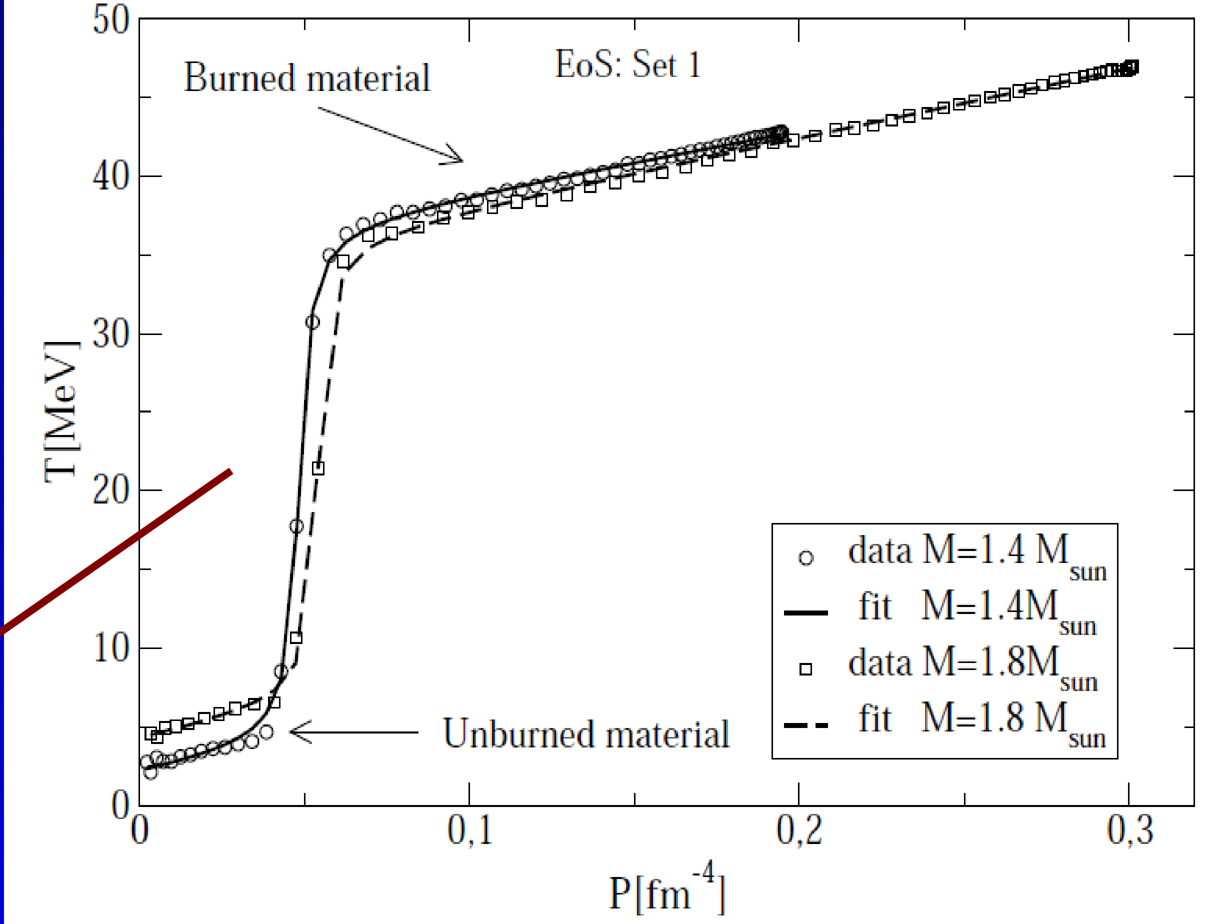
Drago et al 2007



Herzog-Roepke 2012

Temperature profiles after the combustion

The huge energy released in the burning leads to a significant heating of the star, few tens of MeV in the center.



Steep gradient of the temperature

Since the burning occurs on time scales of the order of ms, it is decoupled from the cooling (typical time scales of the order of seconds)

Temperature profiles as initial conditions for the cooling diffusion equation

Heat transport equation due to neutrino diffusion

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{dt}}\frac{\epsilon_{tot}}{n_b} + P\frac{\mathrm{d}}{\mathrm{dt}}\frac{1}{n_b} &= -\frac{\Gamma}{n_b r^2 \mathrm{e}^{\Phi}}\frac{\partial}{\partial r}\left(\mathrm{e}^{2\Phi} r^2 \left(F_{\epsilon,\nu_e}\right.\right. \\
&\quad + \left.\left. F_{\epsilon,\nu_\mu}\right)\right) \\
\frac{dP}{dr} &= -(P+\epsilon_{tot})\frac{m+4\pi r^3 P}{r^2-2mr} \\
\frac{dm}{dr} &= 4\pi r^2 \epsilon_{tot} \\
\frac{da}{dr} &= \frac{4\pi r^2 n_b}{\sqrt{1-2m/r}} \\
\frac{d\Phi}{dr} &= \frac{m+4\pi r^3 P}{r^2-2mr}
\end{aligned}
$$

$$
\begin{aligned}
F_{\epsilon,\nu_e} &= -\frac{\lambda_{\epsilon,\nu_e}}{3}\frac{\partial \epsilon_{\nu_e}}{\partial r} \\
F_{\epsilon,\nu_\mu} &= -\frac{\lambda_{\epsilon,\nu_\mu}}{3}\frac{\partial \epsilon_{\nu_\mu}}{\partial r}
\end{aligned}
$$

Assumption: quark matter is formed already in beta equilibrium, no lepton number conservation imposed in the burning simulation, no lepton number diffusion

$\downarrow$

Diffusion is dominated by scattering of non-degenenerate neutrinos off degenerate quarks

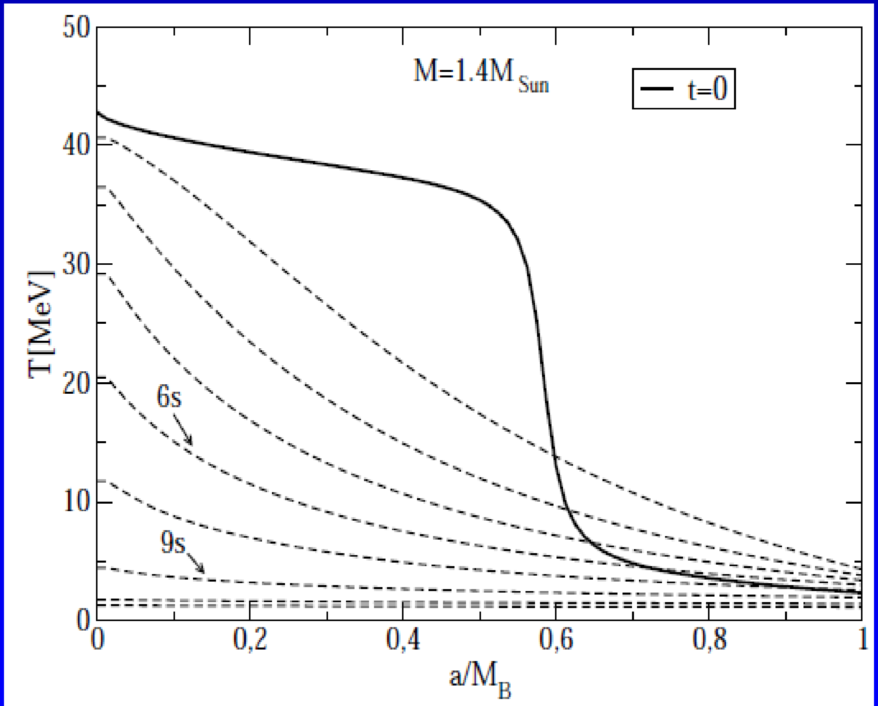
$$\frac{\sigma_S}{V} = \frac{G_F^2 E_\nu^3 \mu_i^2}{5\pi^3}$$

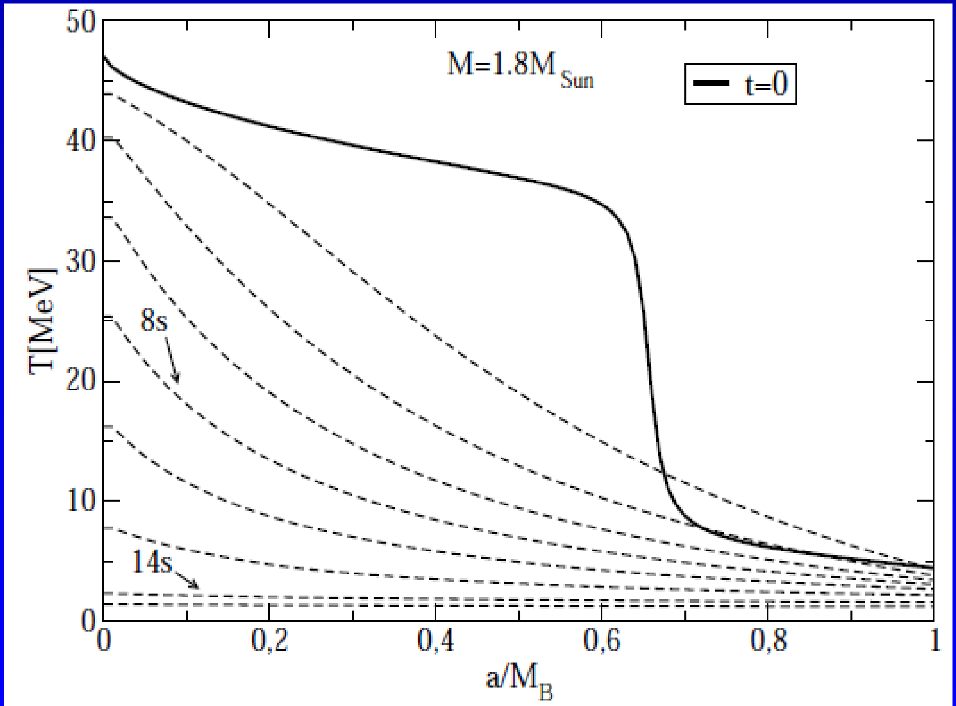
Steiner et al 2001

Expected smaller cooling times with respect to hot neutron stars

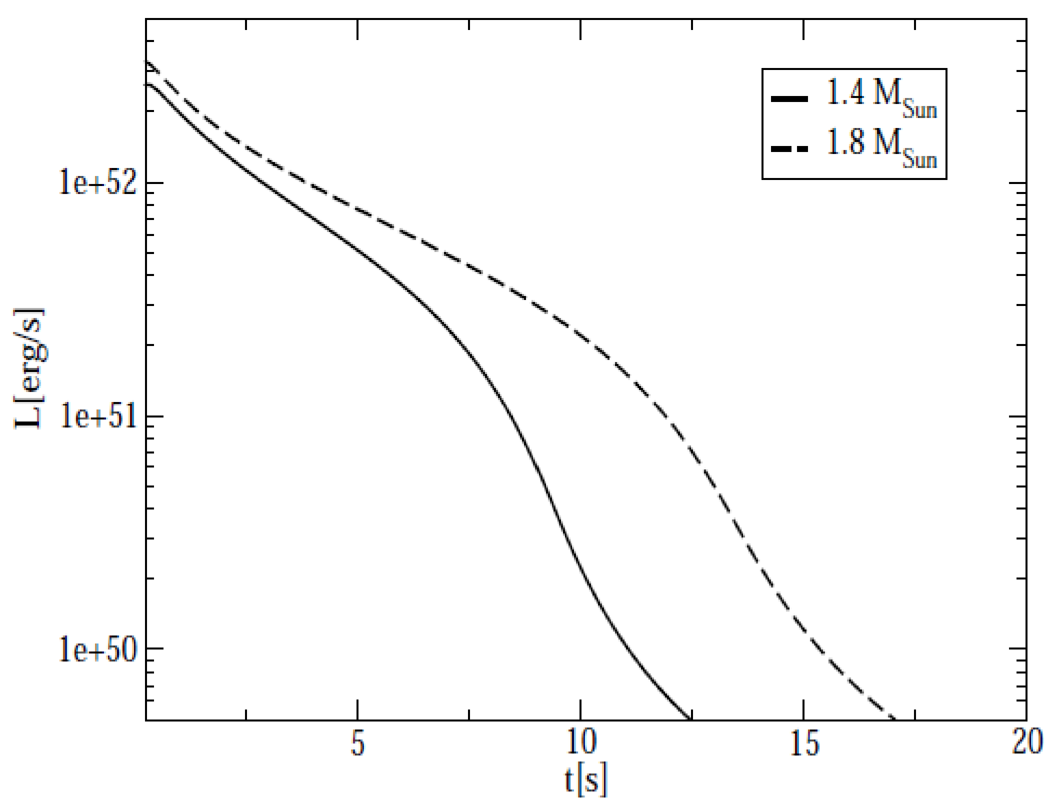
phase	process	λ(T=5 MeV)	λ(T=30 MeV)
Nuclear Matter	$\nu n \to \nu n$	200 m	1 cm
	$\nu_e n \to e^- p$	2 m	4 cm
Unpaired Quarks	$\nu q \to \nu q$	350 m	1.6 m
	$\nu d \to e^- u$	120 m	4 m
CFL	λ_{3B}	100 m	70 cm
	$\nu\phi \to \nu\phi$	>10 km	4 m

Reddy et al 2003





Luminosity curves similar to the protoneutron stars neutrino luminosities. Possible corrections due to lepton number conservation...



Phenomenology I: such a neutrino signal could be detected for events occurring in our galaxy (possible strong neutrino signal lacking the optical SN counterpart if the conversion is delayed wrt the SN)

Phenomenology II: connection with double GRBs within the protomagnetar model

UNUSUAL CENTRAL ENGINE ACTIVITY IN THE DOUBLE BURST GRB 110709B

Bin-Bin Zhang[1], David N. Burrows[1], Bing Zhang[2], Peter Mészáros[1,3], Xiang-Yu Wang[4,5], Giulia Stratta[6,7], Valerio D'Elia[6,7], Dmitry Frederiks[8], Sergey Golenetskii[8], Jay R. Cummings[9,10], Jay P. Norris[11], Abraham D. Falcone[1], Scott D. Barthelmy[12], Neil Gehrels[12]

Draft version January 17, 2012

ABSTRACT

The double burst, GRB 110709B, triggered *Swift*/BAT twice at 21:32:39 UT and 21:43:45 UT, respectively, on 9 July 2011. This is the first time we observed a GRB with two BAT triggers. In this paper, we present simultaneous *Swift* and Konus-*WIND* observations of this unusual GRB and its afterglow. If the two events originated from the same physical progenitor, their different time-dependent spectral evolution suggests they must belong to different episodes of the central engine, which may be a magnetar-to-BH accretion system.

Subject headings: gamma-ray burst: general

Conclusions

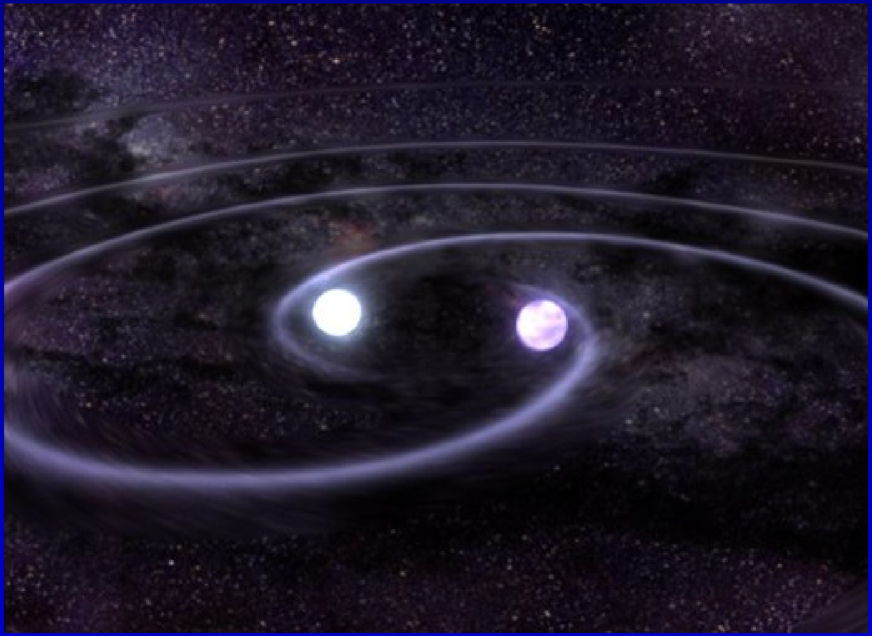
-) New masses and radii measurements challenge nuclear physics: tension between high mass and small radii. A 2.4 Msun candidate already exists. Delta resonances must be taken into account when computing the equation of state (if L is <about 70 MeV): “Delta isobars puzzle”

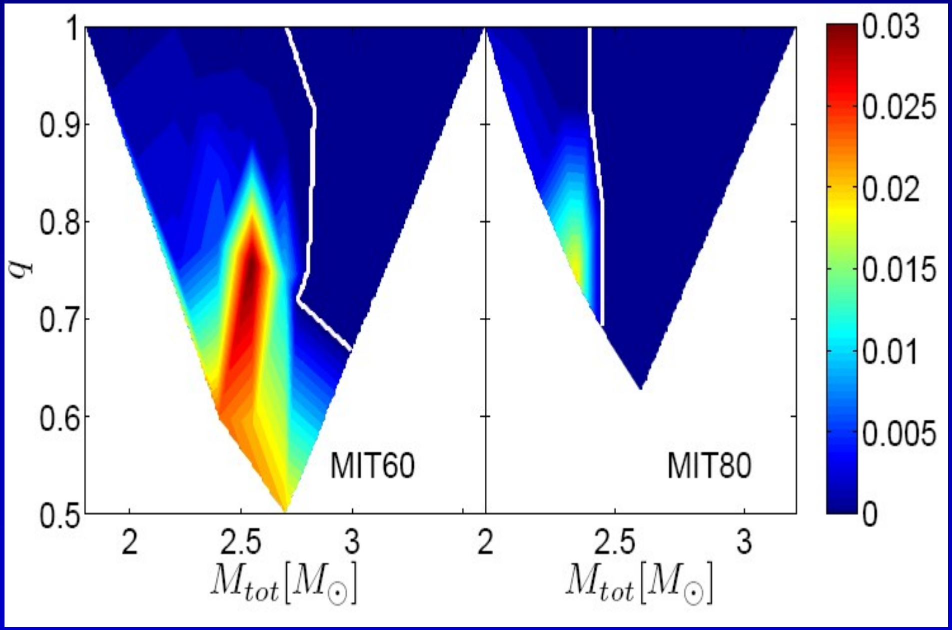
-) LOFT and NICER missions, with a precision of 1km in radii measurements, could hopefully solve the problem: small radii if confirmed seem to indicate the existence of two families of CSs

-) Possible existence of two families of compact stars: (high mass – quark stars, low mass – hadronic stars). Rich phenomenolgy: cooling, frequency distributions, explosive events...

Appendix

Are all CSs QSs ?: Merger of strange stars





MIT60: $8 \times 10^{-5} M_{sun}$, MIT80 no ejecta. By assuming a galactic merger rate of $10^{-4(-5)}$/year, mass ejected: $10^{-8(-9)} M_{sun}$/year. Constraints on the strangelets flux (for AMS02)

A. Bauswein et al PRL (2009)

Appendix2

$$
\begin{aligned}
(e_h + p_h) v_h \gamma_h^2 &= (e_q + p_q) v_q \gamma_q^2 \,, \\
(e_h + p_h) v_h^2 \gamma_h^2 + p_h &= (e_q + p_q) v_q^2 \gamma_q^2 + p_q \,,
\end{aligned}
$$

Taub adiabat

$$\rho_B^h v_h \gamma_h = \rho_B^q v_q \gamma_q$$

$$\Delta \left(\frac{E}{A}\right)(T, \rho_B^h) \equiv \frac{e_h(u_h, \rho_B^h, T_h)}{\rho_B^h(u_h)} - \frac{e_q(u_q, \rho_B^q, T)}{\rho_B^q(u_q)} = c_V^q (T - T_h)$$

If >0 exothermic process

Drago et al 2007

Temperature dependence of the mass