Conversion of hadronic stars into quark stars: the turbulent and the diffusive regimes

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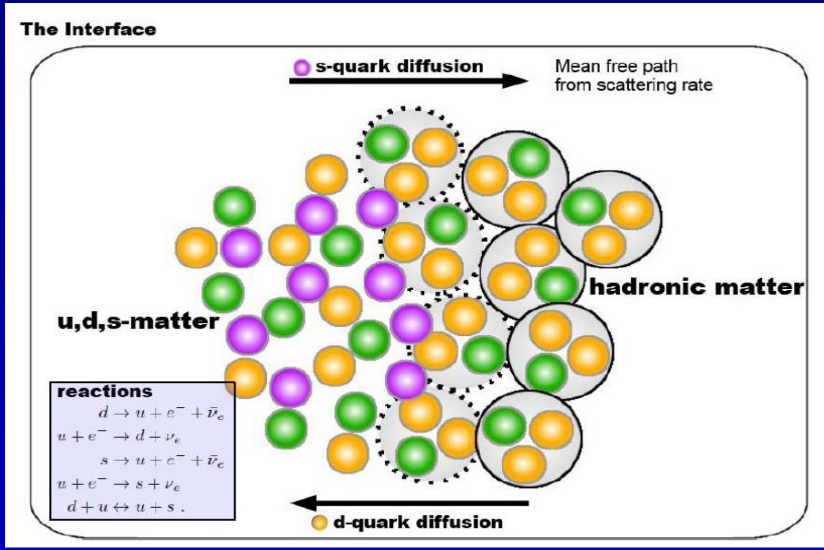
Outline

- **-) Modeling the birth of quark star as a combustion process**
- **-) Numerical simulations**
- **-) Neutrino signal estimates**
- **-) Two families scenario**

Combustion process

Within the Witten's hypothesis (but a similar model can be used also for hybrid stars), the process of conversion of a hadronic star into a quark star can be treated as a combustion



Refs: Olinto 1987, Lugones 1994, Drago 2007, Niebergal 2010, Herzog 2011, G.P. 2013...

Kinetic theory approach

$$D_{\rm Q}\, a'' - v_{\rm N\to Q}\, a' - \mathcal{R}_{\rm Q}(a) = 0,$$
$$\mathcal{R}_{\rm Q}(a) = (\Gamma_{\rm d\to s} - \Gamma_{\rm s\to d})/n_{\rm Q},$$

Typical burning velocity: v~sqrt(D/ τ) ~ 10^4 cm/s and scale as T^(-5/6)

Microphysics: "a" strangeness fraction (n.down-n.strange)/n.baryons

Diffusion coefficient:

$$D \simeq 10^{-1} \left(\frac{\mu_f}{300\ {\rm MeV}}\right)^{2/3} \left(\frac{T}{10\ {\rm MeV}}\right)^{-5/3} {\rm cm}^2/s$$

Typical time scale for u+d->u+s

$$\tau_{\rm Q} \simeq 1.3 \times 10^{-9}\, {\rm s}\ (300\, {\rm MeV}/\mu_{\rm Q})^5$$

Typical width of the combustion zone: δ~sqrt(D τ) ~ 10^{-5} cm thus very small in comparison with the size of a star

Coupling with hydrodynamics

Ouyed 2010: 1D – no gravity – no star!

The 1-D hydrodynamical equations in our case are [24]:

$$\frac{\partial U}{\partial t} = -\nabla F(U) + \mathcal{S}(U) \ , \quad (1)$$

with variables

$$U = \begin{pmatrix} n_s \\ n_s + n_d \\ n_s + n_d + n_u \\ hv \\ s \end{pmatrix} , \quad (2)$$

and corresponding advective-diffusive terms

$$F(U) = \begin{pmatrix} vn_s + D\nabla n_s \\ v(n_s + n_d) \\ v(n_s + n_d + n_u) \\ hv^2 + P \\ vs \end{pmatrix} , \quad (3)$$

and source terms

$$\mathcal{S}(U) = \begin{pmatrix} -\Gamma_3 + \Gamma_4 + \Gamma_5 \\ -\Gamma_1 + \Gamma_2 - \Gamma_3 + \Gamma_4 \\ 0 \\ 0 \\ -\frac{1}{T}\sum_i \mu_i \frac{dn_i}{dt} \end{pmatrix} . \quad (4)$$

Such a calculation would be impossible in 2 or 3D which are needed to study the possible occurrence of hydrodynamical instabilities.

A similar problem when simulating type Ia SN.
Two possible strategies:
1) Khokhlv 1993:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{U}) \ ,$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} = -\nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) - \nabla P + \rho \boldsymbol{g} \ ,$$

$$\frac{\partial E}{\partial t} = -\nabla \cdot [(E + P)\boldsymbol{U}] + \rho \boldsymbol{U} \cdot \boldsymbol{g} + \rho \dot{Q} \ ,$$

$$\frac{\partial f}{\partial t} + \boldsymbol{U} \cdot \nabla f = K\nabla^2 f + R$$

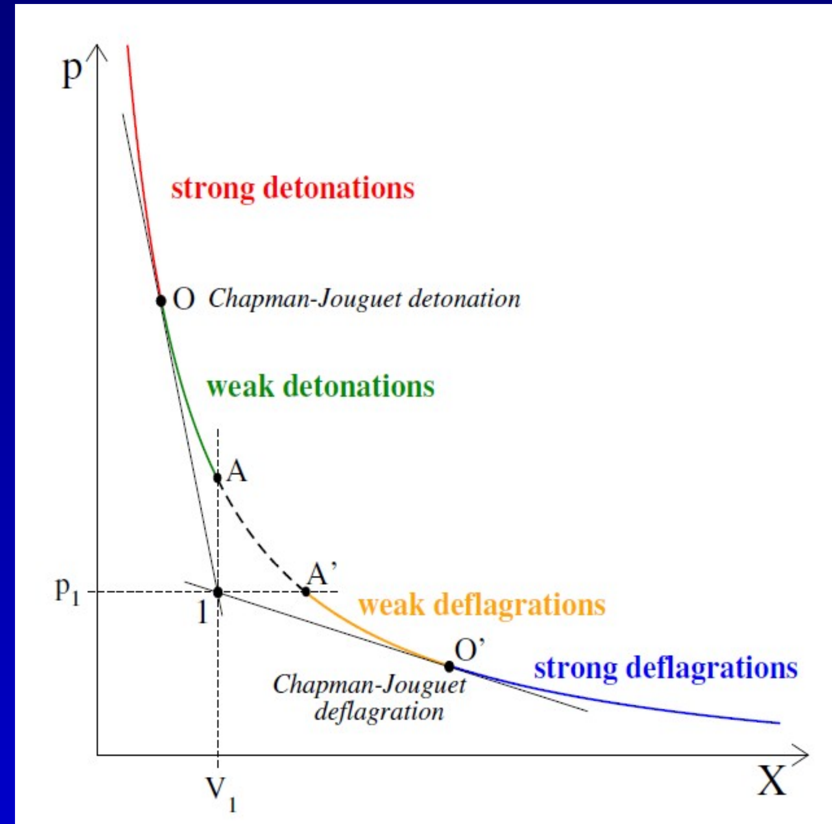
K and R are rescaled to enlarge the width of the combustion zone over several computational cells. It underestimates hydro-instabilities

2) Calculate the burning velocities profiles from the microscopic model, assume an infinitely thin combustion layer.
Hillebrandt 1999

Stationary hydro, two fluids separated by a surface of discontinuity

$w_1\gamma_1^2 v_1 = w_2\gamma_2^2 v_2$	T_{0x}
$p_1 + w_1 v_1^2\gamma_1^2 = p_2 + w_2 v_2^2\gamma_2^2$	T_{xx}
$n_1 v_1\gamma_1 = n_2 v_2\gamma_2 \equiv j$	particles flux

From microscopic theory



Depending on the EoS of the two fluids and j one can obtain all the different combustion modes.

Several calculations (see Drago 2007) have shown that in the case of burning of hadronic stars, detonations are quite unlikely. The combustion proceeds as a deflagration.

Numerical simulations of Herzog- Roepke 2011:

-)3+1D code used for SN type Ia simulations
-) Newtonian dynamics + use of an effective relativistic gravitational potential based on TOV (Marek 2006)
-) assume that the combustion proceeds as a deflagration
-) velocity profile taken from Ouyed 2010
-) initial seed: a quark core of 1km which is perturbed with a sinusoidal perturbation of amplitude 0.2 km.
-) EoS: Lattimer-Swesty + MIT bag model
-) 128 or 192 grid cells in each dimension

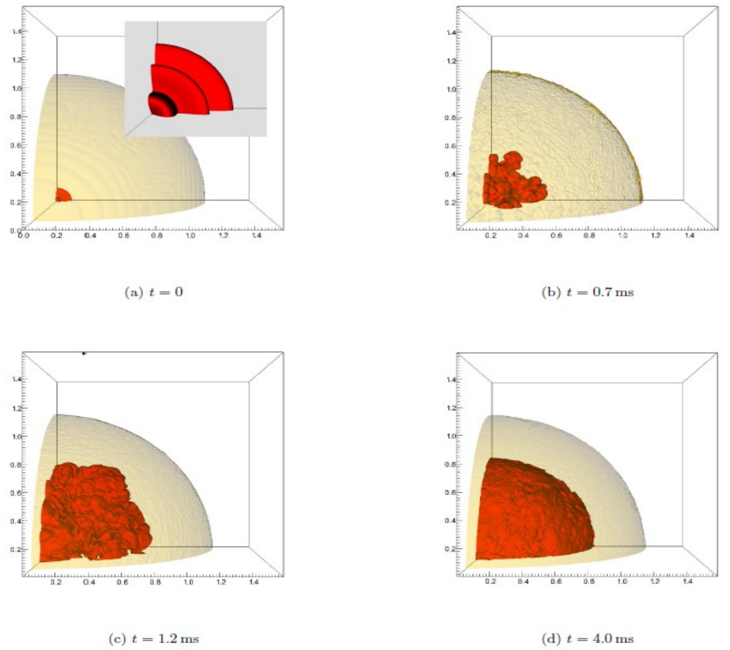


FIG. 8. (color online) Model B150_192: Conversion front (red) and surface of the neutron star (yellow) at different times t. In (a) a close-up of the central region is added. Spatial units 10^6 cm.

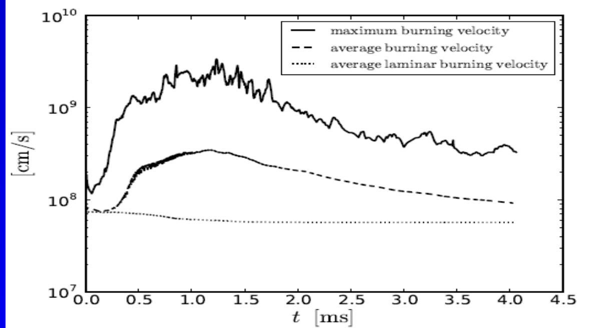
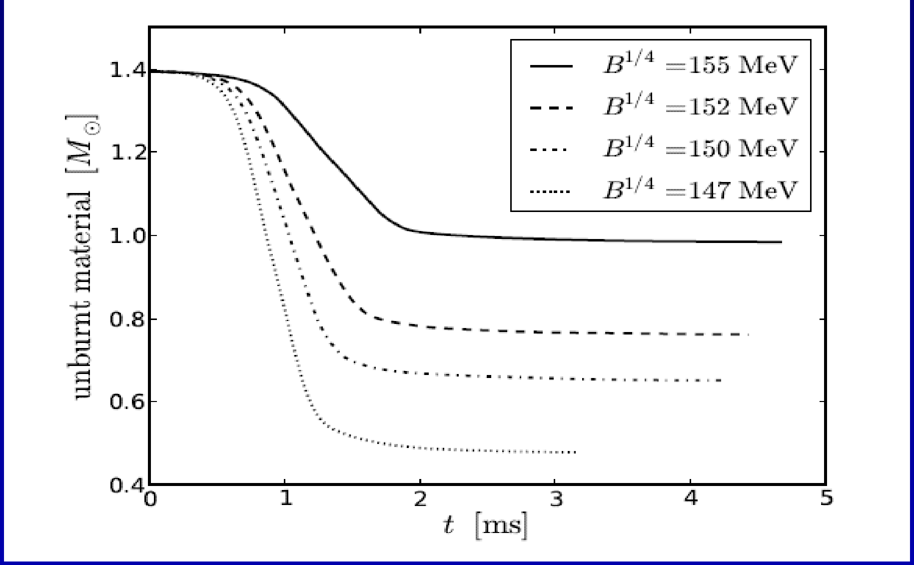


FIG. 7. Burning velocity: Comparison at each timestep of maximum burning velocity, average burning velocity and the underlying average laminar burning velocity. The averages where done over all cells in which burning occurs. Data from the high resolution run with $B^{1/4} = 150$ MeV (model B150_192).

Time needed for the partial conversion: few ms, burning velocities substantially increased by RT- instabilities.

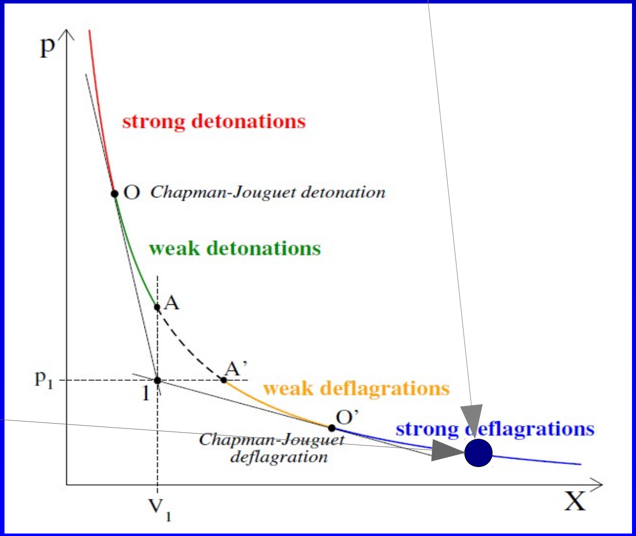
Some material, few 0.1 Msun, is left unburnt.



Coll's condition for "exothermic" combustion (1976), the energy density of the fuel must be larger than the energy density of the ashes at the same pressure p and dynamical volume X

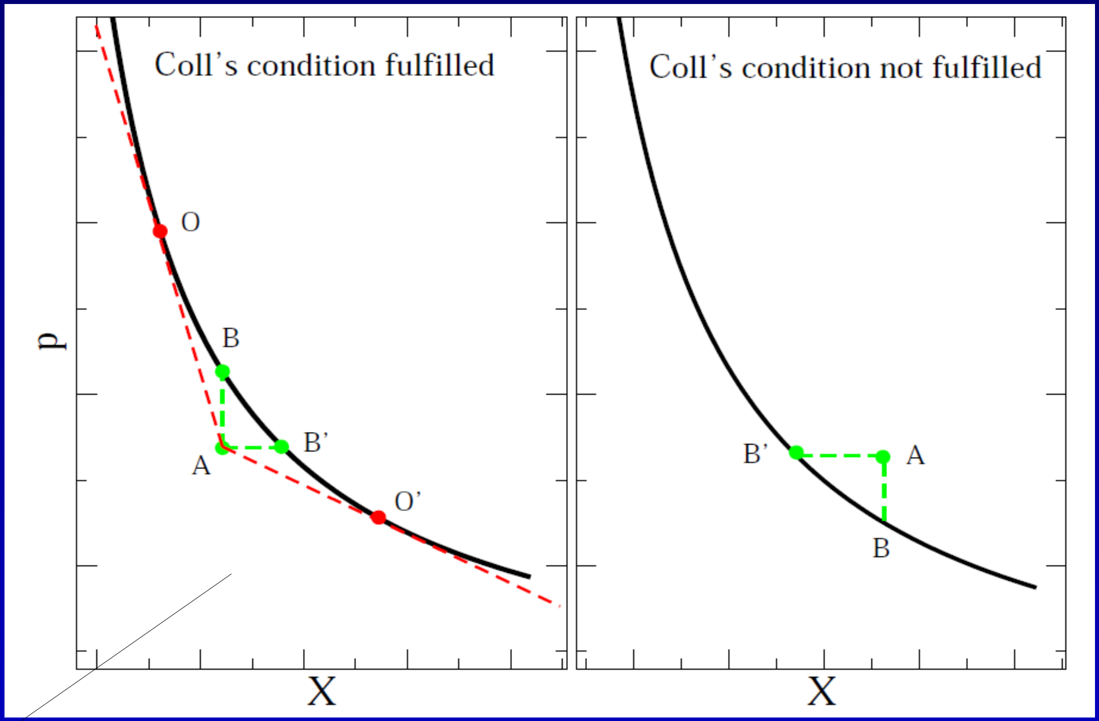
$$e_h(P, X) > e_q(P, X),$$

The initial point lies on the detonation adiabat:



There is a critical density n_crit for which the the turbulent hydro-conversion stops

Let us consider the case of a slow combustion (in 1+1D): Coll's condition implies that the new phase (quark) is produced at a baryon density and a energy density smaller then the old phase (hadronic). Inverse density stratification: within the star the gravitational potential and the density gradient point in opposite directions



The front velocity is increased by R-T instabilites

$$v_{mh} = v_{lh} (\lambda_{\max}/\lambda_{\min})^{\Delta D}$$

$$\gamma = 1 - \frac{e_2}{e_1}.$$

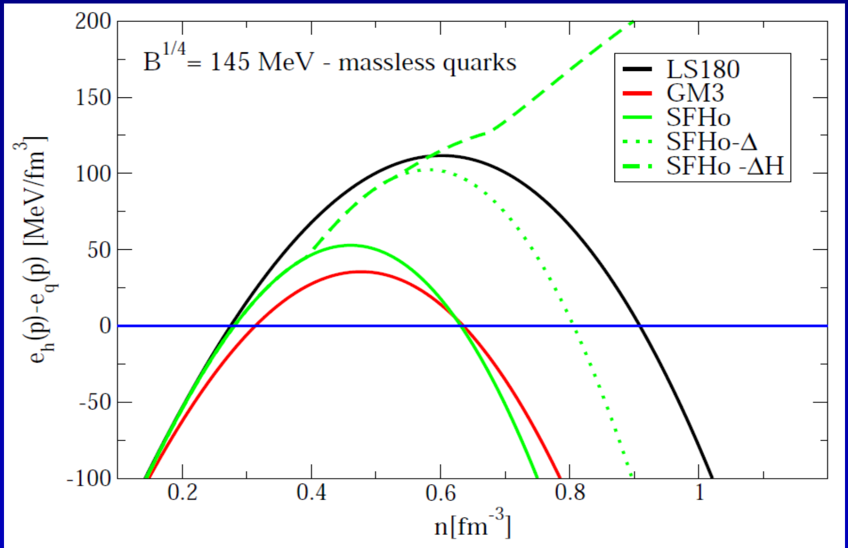
$$\Delta D = D_0 \gamma^2$$

Fractal dimension ΔD

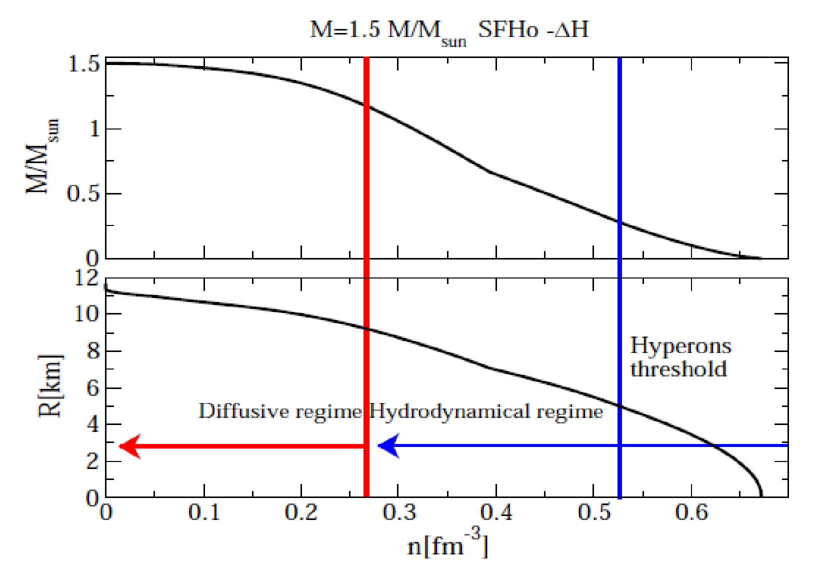
At densities smaller than n_crit the combustion can proceed but the quark phase is more dense than the hadronic phase. R-T instabilities not active anymore. The conversion velocity coincides with the laminar velocity. Diffusive regime: time scales much longer than the ones of the turbulent regime.

Modeling the diffusive regime

For different hadronic equations of state n_crit ~ 0.2 0.3 fm^-3 (example of massless quarks)

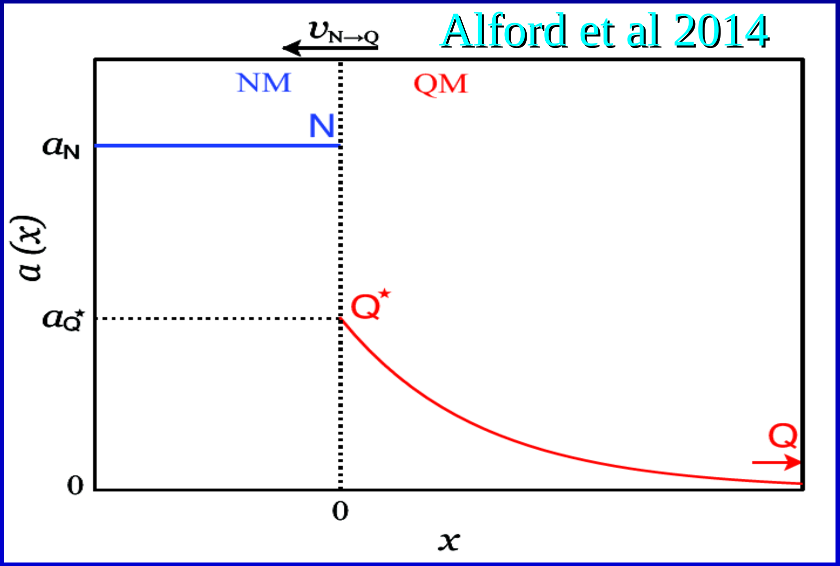


Profile of a 1.5 hadronic star: turbulent conversion can start once hyperons appear, and it will stop 2km below the surface of the star leaving 0.3 Msun which will burn during the diffusive regime.



Within the combustion layer: diffusion and flavor changing weak interactions among quarks

$$D = 0.1\left(\frac{\mu_q}{300\,\mathrm{MeV}}\right)^{2/3}\left(\frac{T}{10\,\mathrm{MeV}}\right)^{-5/3}\mathrm{cm}^2/\mathrm{sec}, \quad \tau = 1.3\times10^{-9}\left(\frac{300\,\mathrm{MeV}}{\mu_q}\right)^5\mathrm{sec}$$



$$v_{lh} = \sqrt{\frac{D}{\tau}\frac{a_{Q*}^4}{2a_N(a_N - a_{Q*})}}$$

At fixed pressure, the minimum amount of strangeness (non-beta stable quark matter) for the process of conversion to be energetically favoured

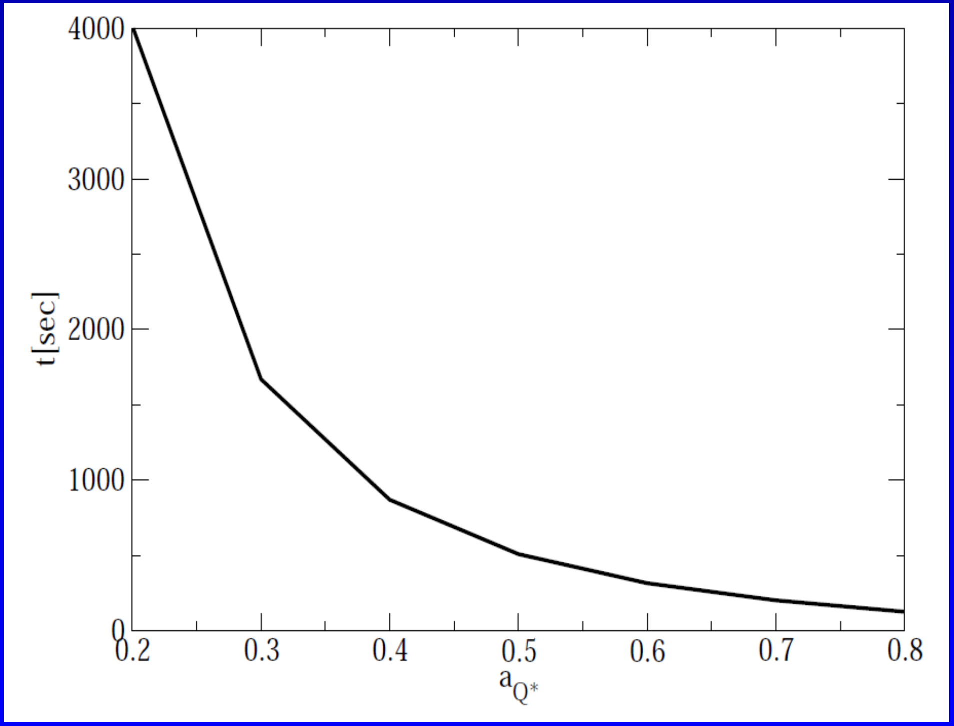
Case 1) no neutrino cooling:
The new phase is produced at the pressure and enthalpy per baryon of the old phase: two equations which allow to determine the quark chemical potential and the temperature of the new phase

$$\frac{dr}{dt} = v_{lh}(\mu_q(r), T(r))$$

r(0) ~ 9km

r: position of the flame front

Time needed to complete the conversion of the hadronic star (upper limit since T is large), long: cooling must be included



Case 2): including cooling
… but in a very schematic way:
-) Uniform temperature, black body emission from the neutrinosphere.

$$C = 2 \times 10^{39} M/M_\odot (T/10^9)\ \mathrm{erg/K}$$

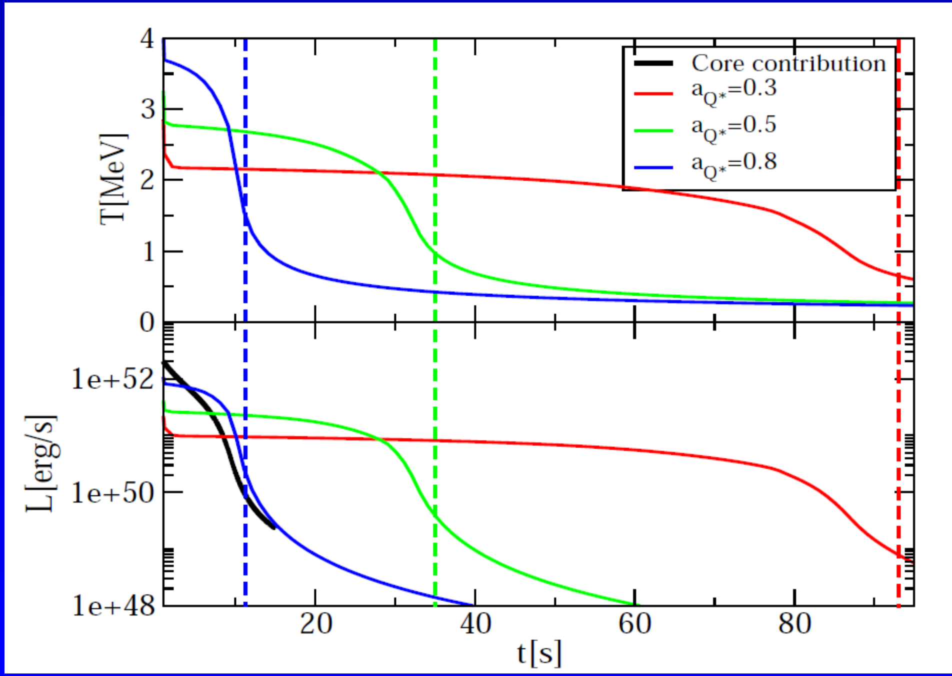
$$L = 21/8\sigma(T/K)^4 4\pi r_s^2$$

$$C(T)\frac{\mathrm{d}T}{\mathrm{d}t} = -L(T) + 4\pi r^2 n_h v_{lh}(\mu_q, T) q$$

$$\frac{\mathrm{d}r}{\mathrm{d}t} = v_{lh}(\mu_q(r), T(r))$$

Energy released by the conversion

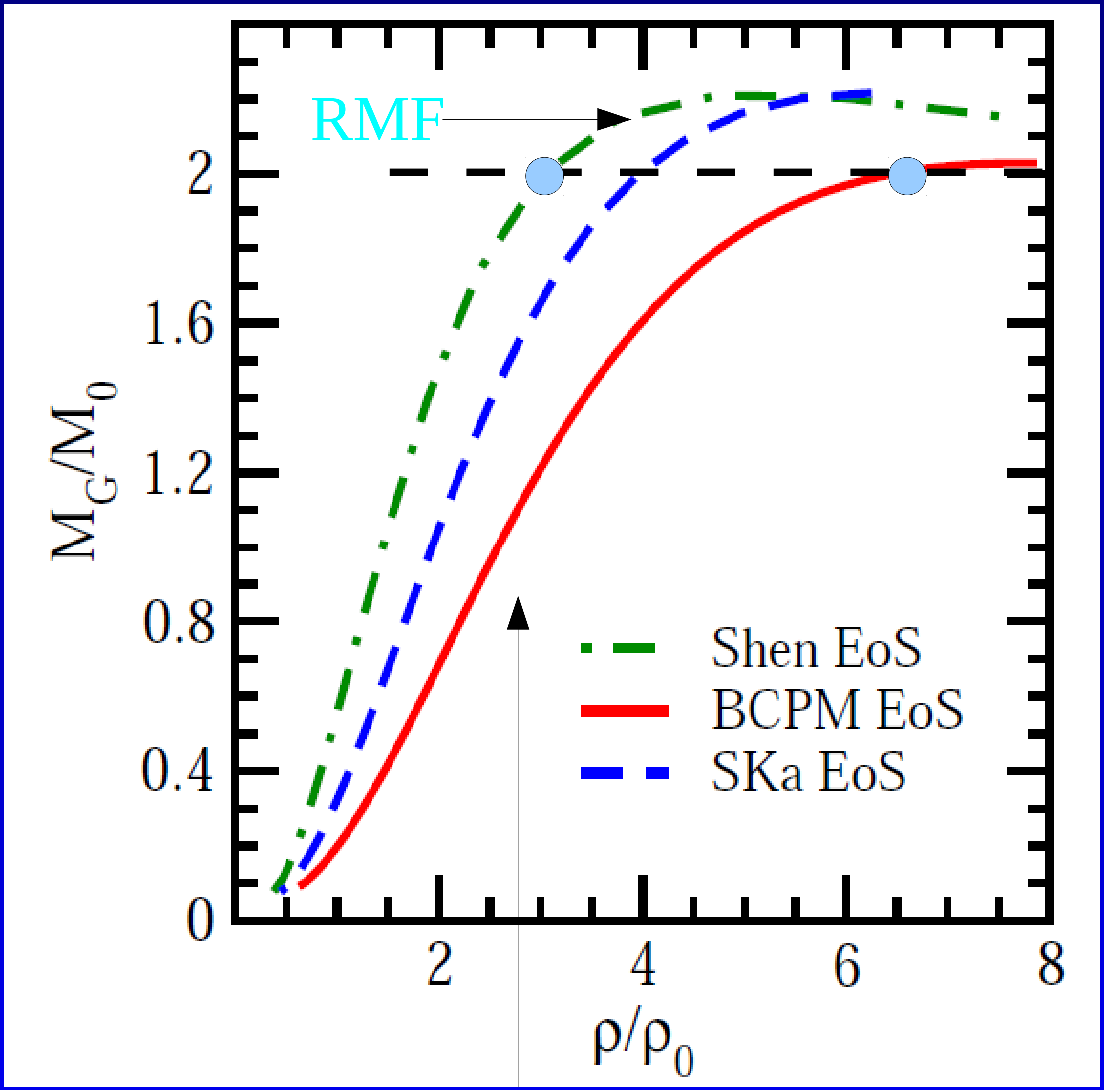
v ~ $1/T^{5/6}$ the more material is converted the higher the temperature the slower the velocity.
Self-regulating mechanism
Plateau in the neutrino luminosity (unique signature for the formation of quark stars).



Why speculating about the existence of quark stars?

What does a 2M_{sun} star mean?

"Standard" neutron stars, just nucleons and electrons.



Central baryon densities of a 2M_{sun} star 3-7 times nuclear saturation density. Are there really just nucleons? Hyperons & Δ ?

Microscopic calculation: nucleon nucleon potential and three body forces (Baldo et al 2013)

Hyperons puzzle (see talk of Francesco and Domenico)

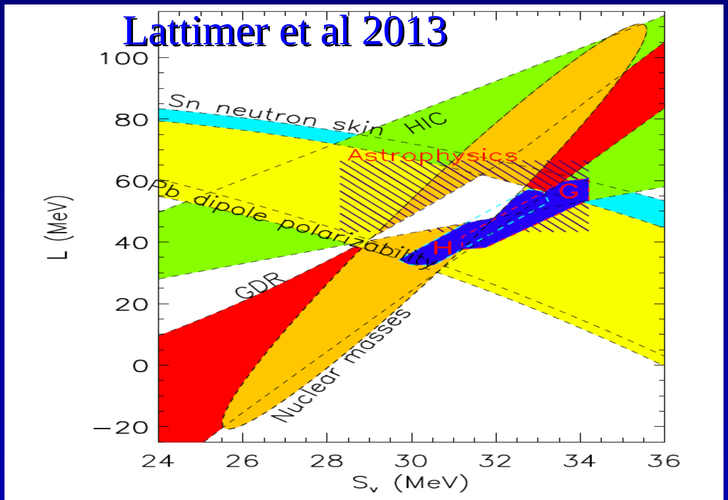
What about delta resonances?

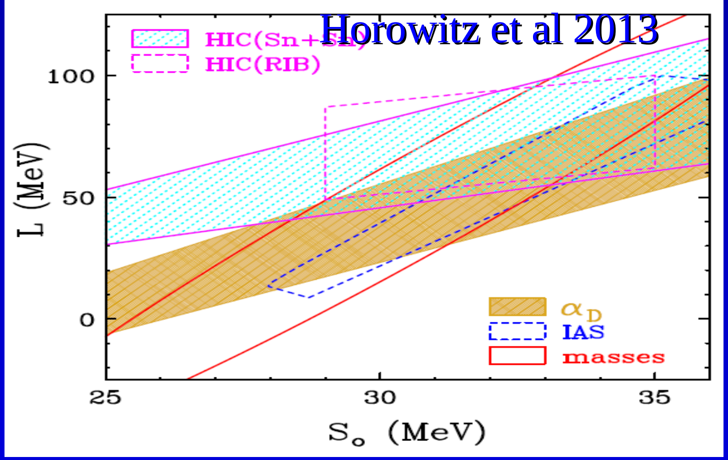
Symmetry energy: the L parameter

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]

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Received 1984 March 28; accepted 1984 December 3

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

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

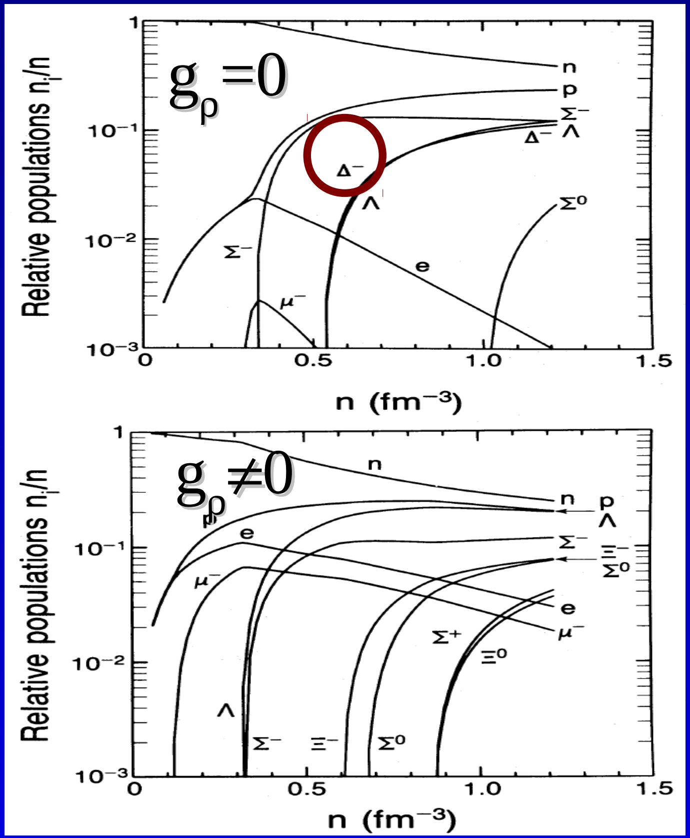
Only S_v could be fixed through g_ρ

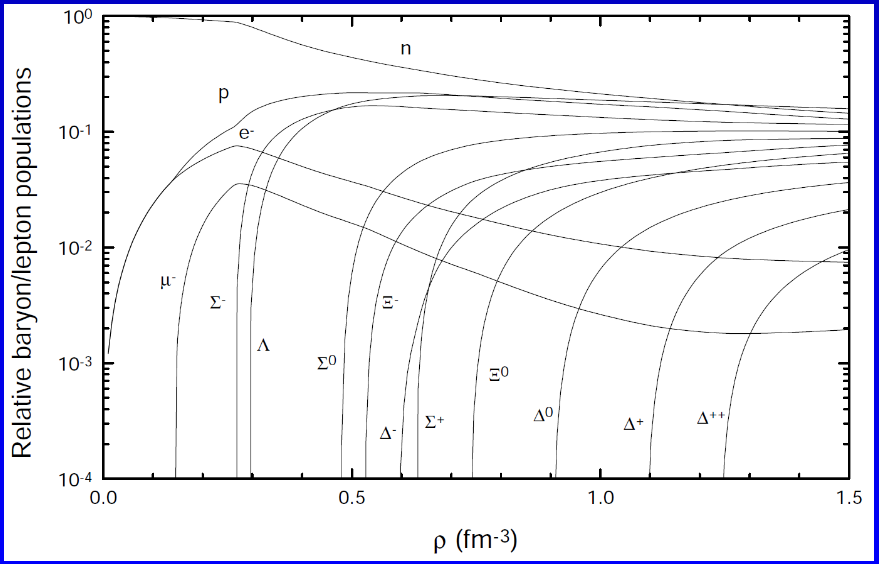
… it turns out that in the GM1-2-3 parametrizations L ~ 80 MeV thus higher than the values indicated by the recent analysis of Lattimer & Lim.

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).



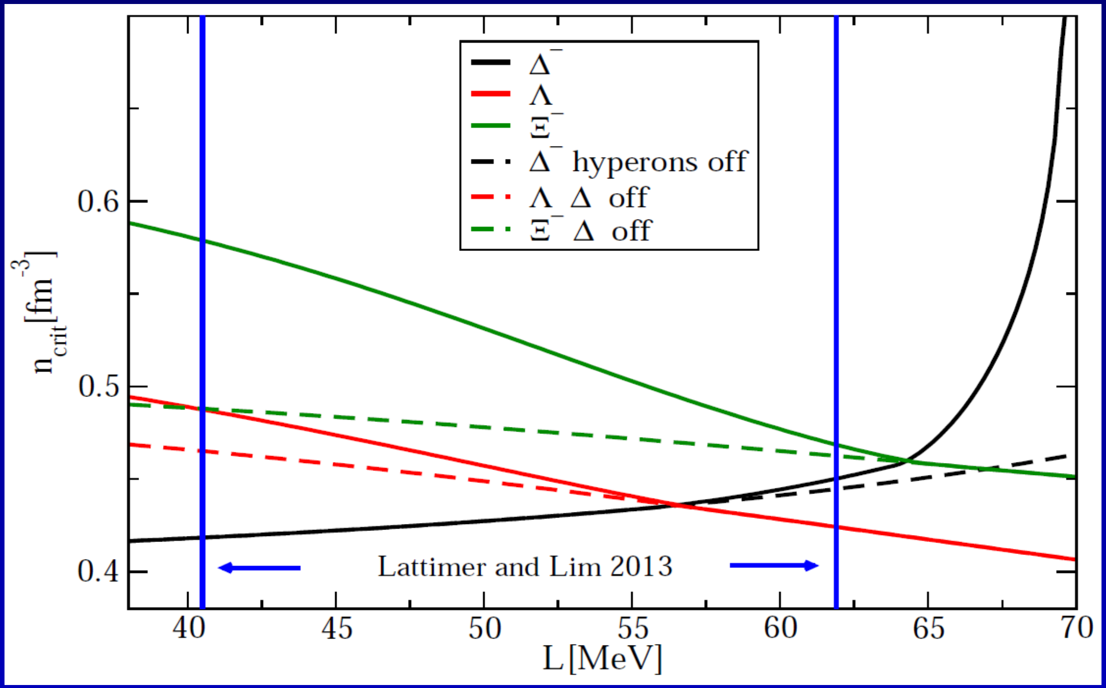


Δ^- easier to form in RHF calculations (see Huber et al 1998) due to the smaller value of g_ρ

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

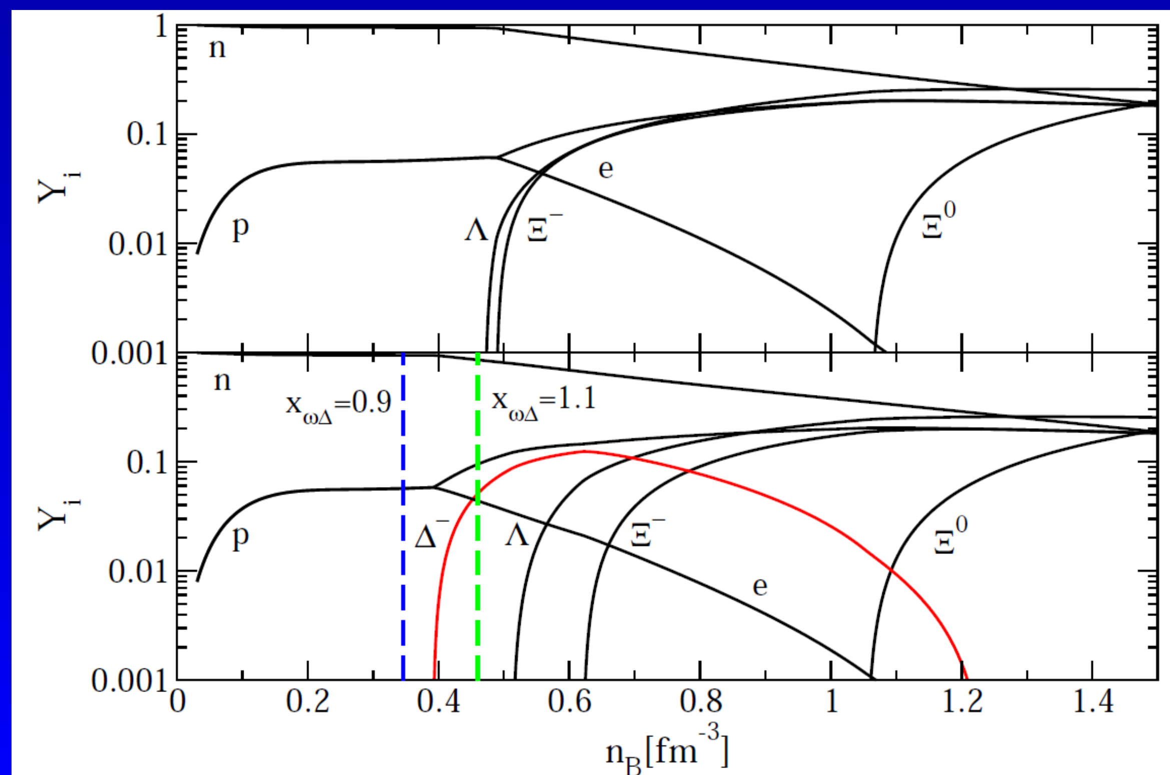
$$\mathcal{L} = \bar{\Psi}\left[i\partial\!\!\!/ - g_\omega \omega\!\!\!/ - \tfrac{1}{2} g_\rho \vec{\rho}\!\!\!/ \cdot \vec{\tau} - M + g_\sigma \sigma - \tfrac{1}{2} e \left(1+\tau_3\right) A\!\!\!/\right]\Psi + \tfrac{1}{2}\left(\partial_\mu \sigma\right)^2 - V(\sigma) - \tfrac{1}{4} f_{\mu\nu} f^{\mu\nu}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

Steiner et al 2005

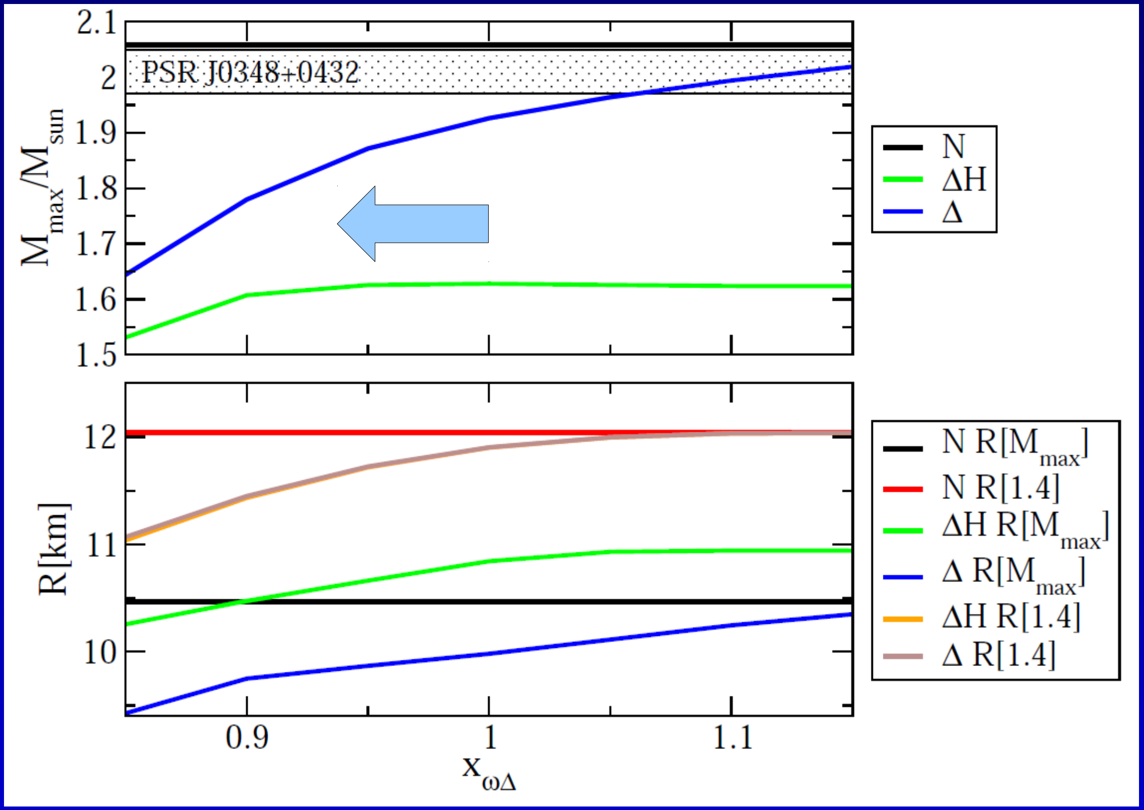
PROPERTIES AT SATURATION DENSITY AND NEUTRON STAR PROPERTIES FOR THE THE DIFFERENT EOSS UNDER INVESTIGATION. THE DEFINITION OF ALL THE QUANTITIES IS GIVEN IN THE TEXT.

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

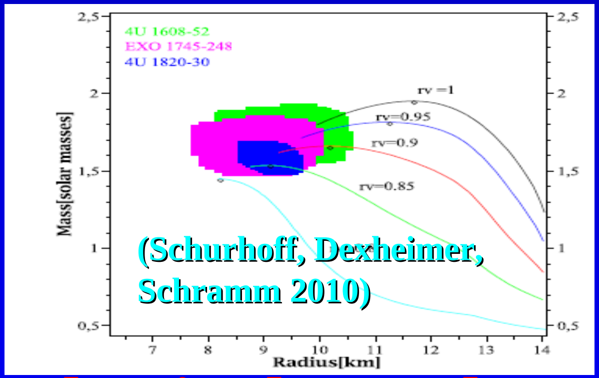
Introducing both hyperons and Δ in the SFHo model: Δ appear before hyperons even in the case of $x_{\omega\Delta} > 1$.



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

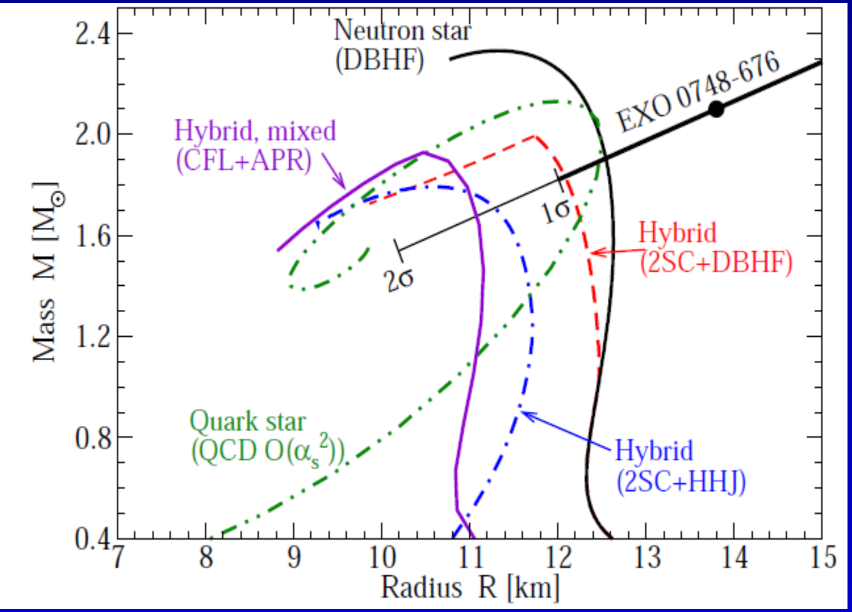


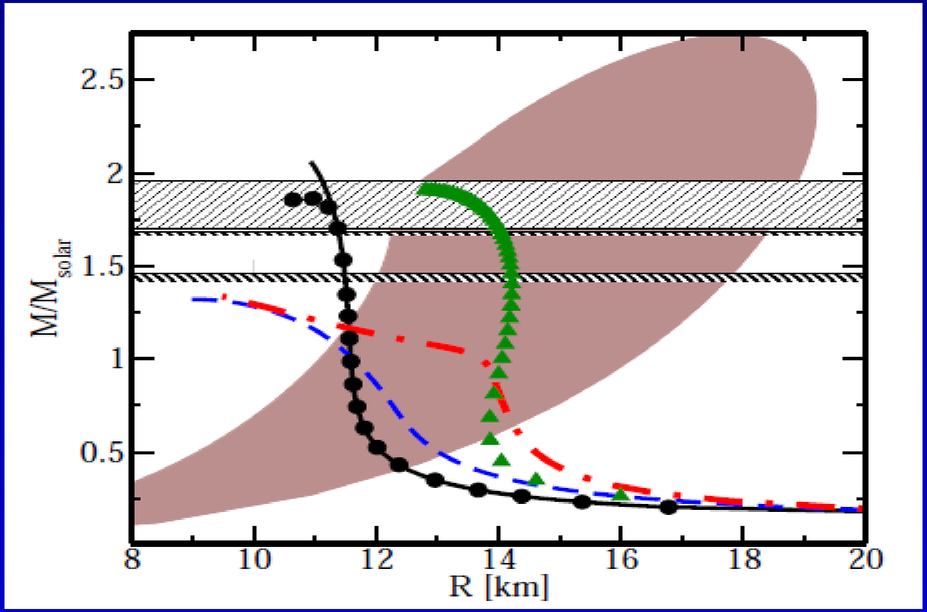
See also:



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

Stars containing quark matter?





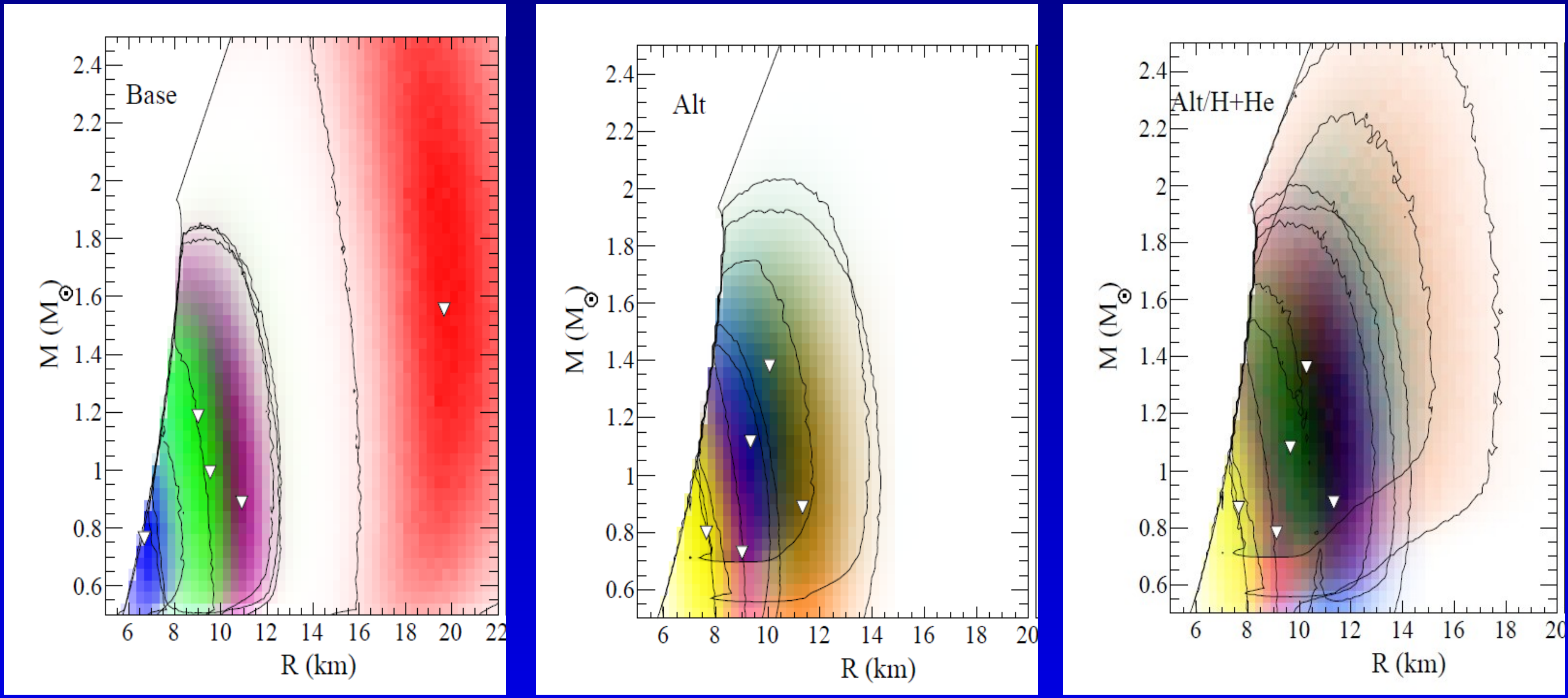
Alford et al Nature 2006

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"

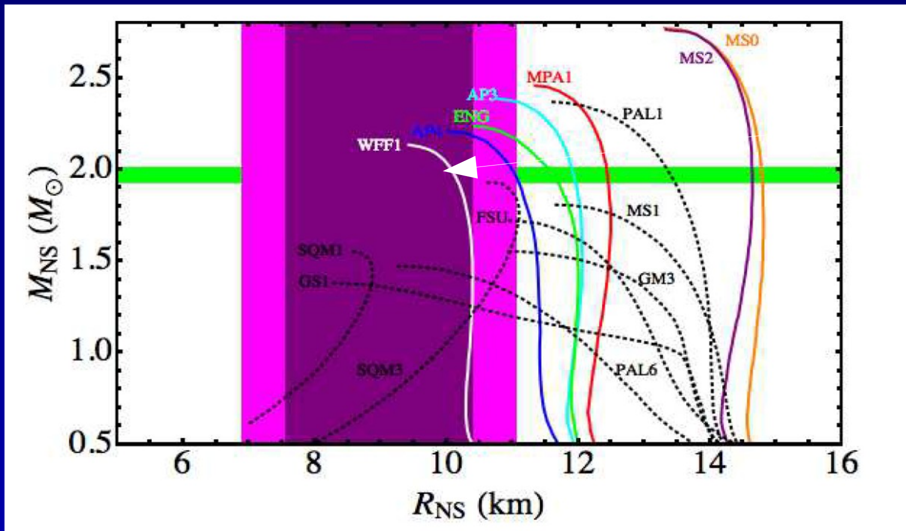
Before the discoveries of the two 2M$_{sun}$ stars!!

Recent radii measurements

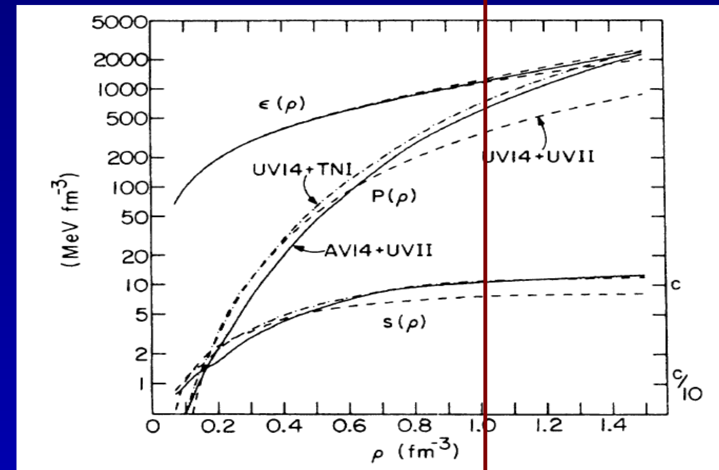


Guillot et al. ApJ772(2013)7

Lattimer and Steiner 1305.3242

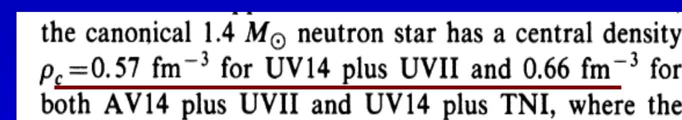


Wiringa et al 1988, nice, but:



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 ρ_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

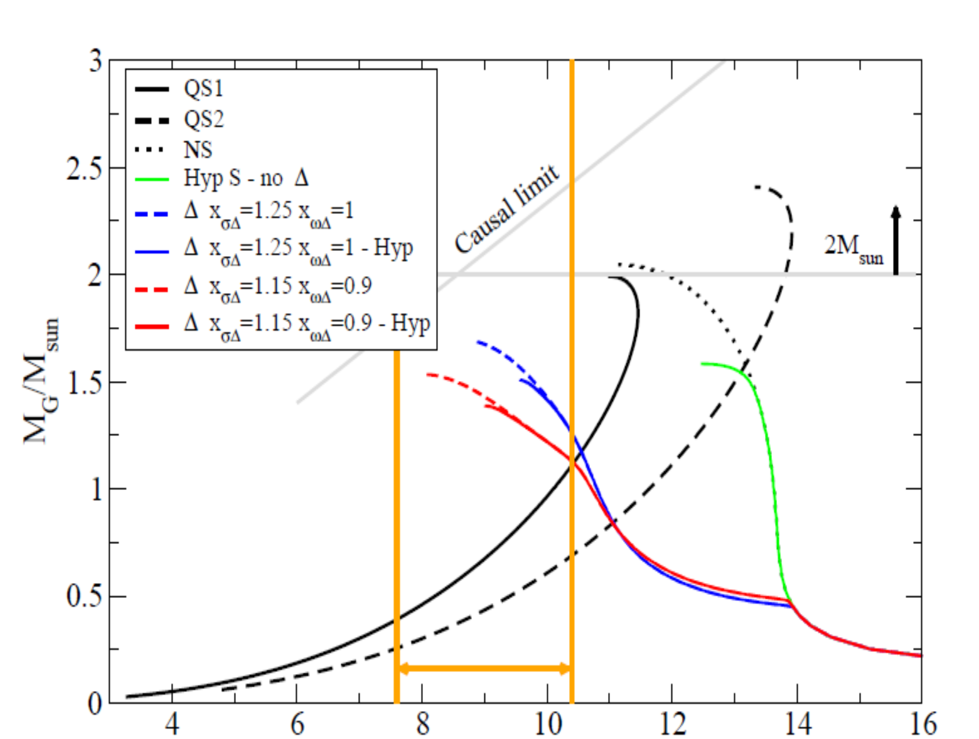
Only nucleons up to very large densities.
Similarly for AP4

Tension between different measuremets:

high masses → stiff equation of state
small radii → soft equation of state
→ large central densities
→ formation of new particles

Two families of compact stars: Berezhiani et al 2003

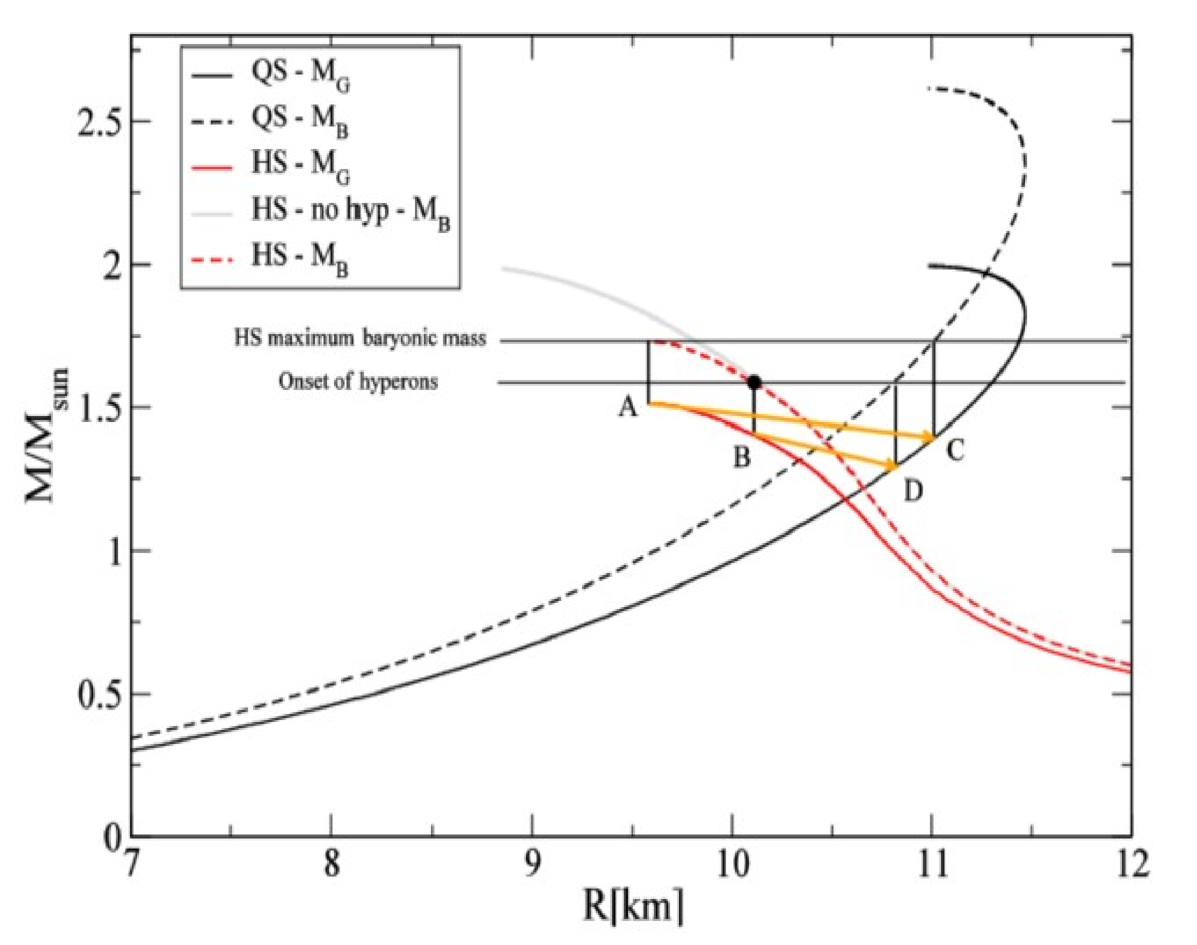
Results from RMF models for hadronic matter and simple parametrizations for quark mater



Drago, Lavagno, G.P. 2013

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.))

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



Conclusions

-) The conversion of an hadronic star into a quark star proceeds via two steps: turbulent regime (time scale ms) – diffusive regime (few s)

-) Burst of neutrinos with a prolongued tail

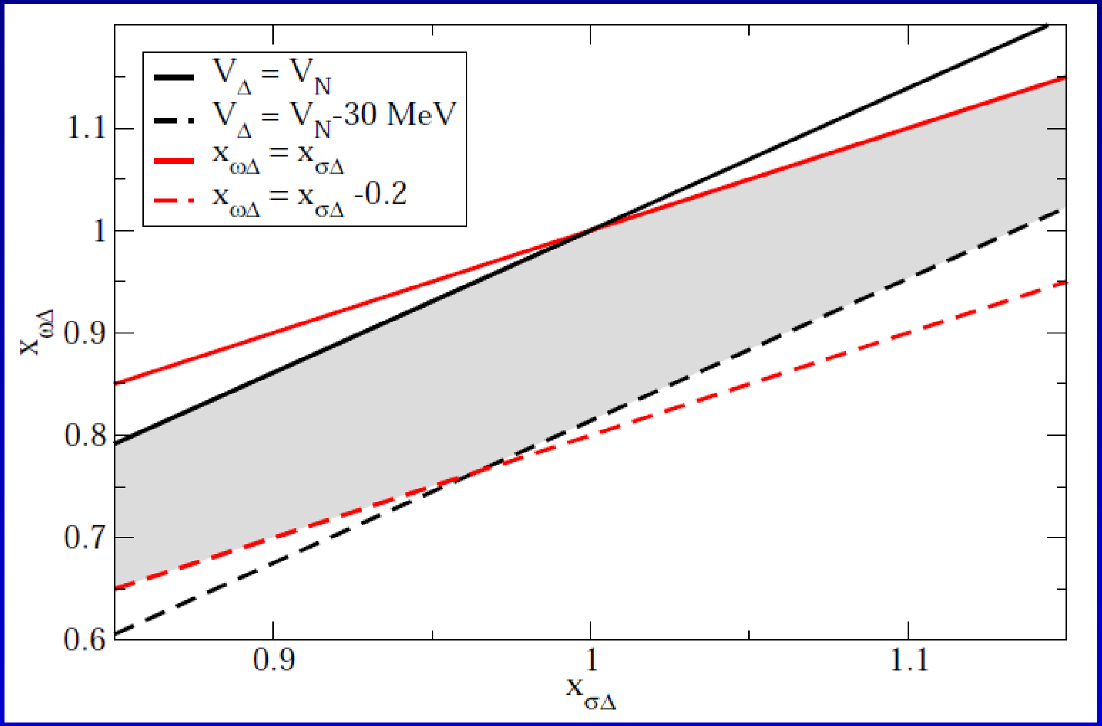
-) New masses and radii measurements challenge nuclear physics: tension between high mass and small radii. A 2.4 M_{sun} candidate already exists.

-) LOFT and NICER missions, with a precision of 1km in radii measurements, could hopefully solve the problem

-) Possible existence of two families of compact stars (high mass – quark stars, low mass – hadronic stars). Rich phenomenolgy: cooling, frequency distributions, explosive events, quark stars are the necessary compact remnant formed during NS mergers (if a BH is not formed promptly).

Appendix

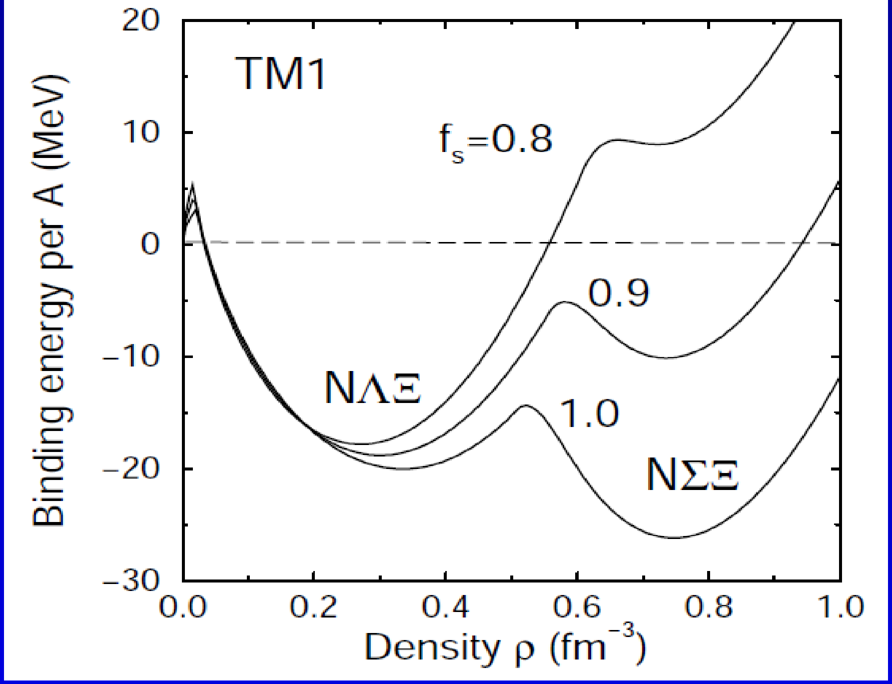
This allows to constrain the free parameters within the RMF model. Notice: coupling with ω mesons suppressed wrt the coupling with the σ meson. The coupling(ratio) with the ρ meson fixed to 1.



Implications for compact stars ?

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)

Hydro simulations to study the conversion

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: 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.

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.

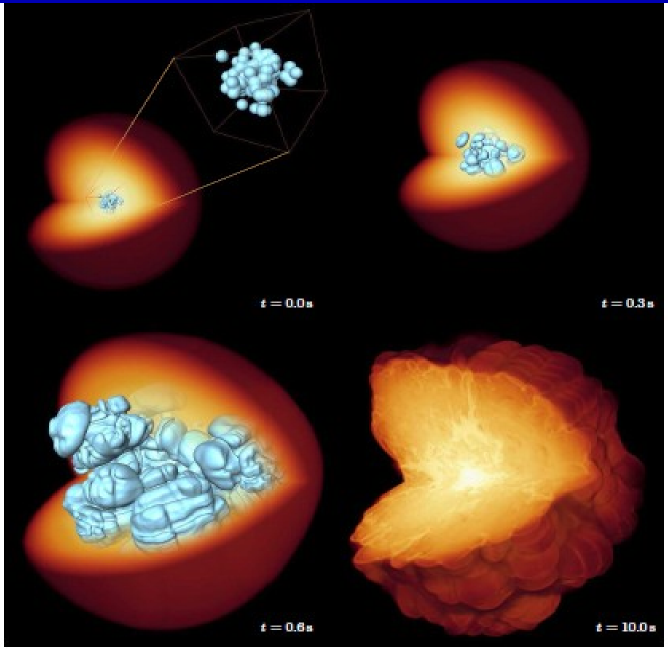


FIGURE 1. Snapshots from a full-star SN Ia simulation starting from a multi-spot ignition scenario. The logarithm of the density is volume rendered indicating the extend of the WD star and the isosurface corresponds to the thermonuclear flame. The last snapshot marks the end of the simulation and is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

Condition for exothermic combustion

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

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

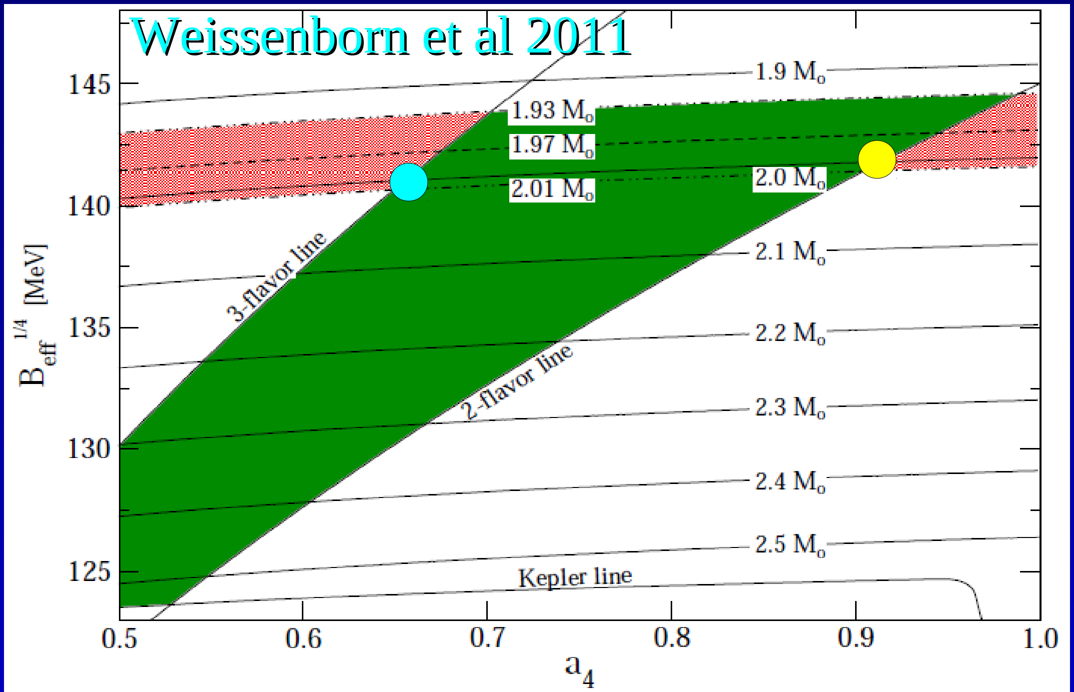
Within a simple parametrization:

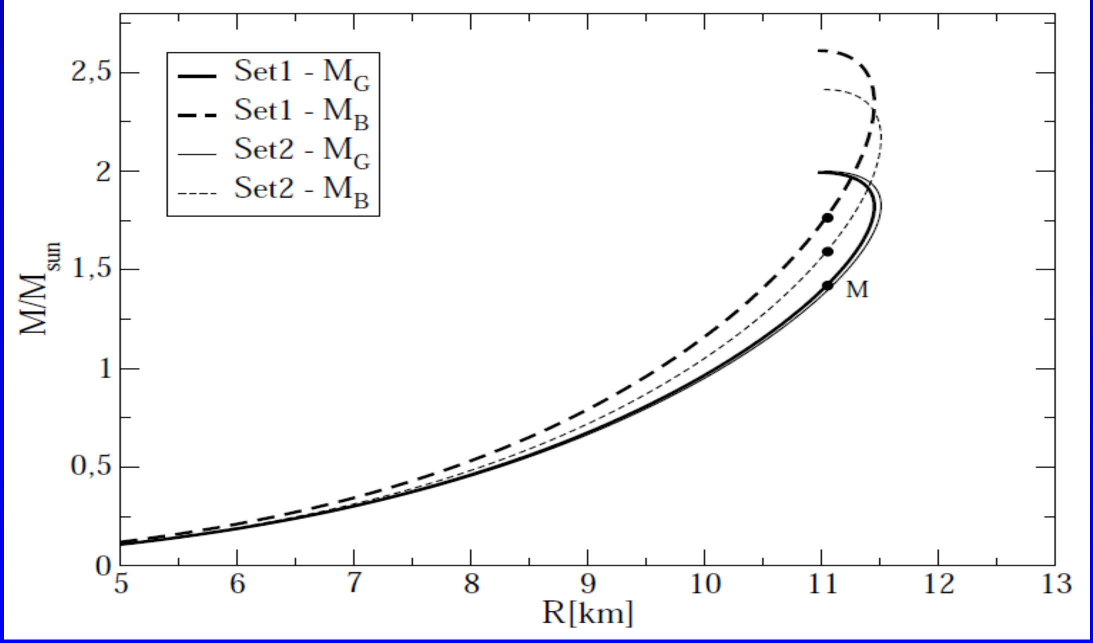
$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B_{eff}$$

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



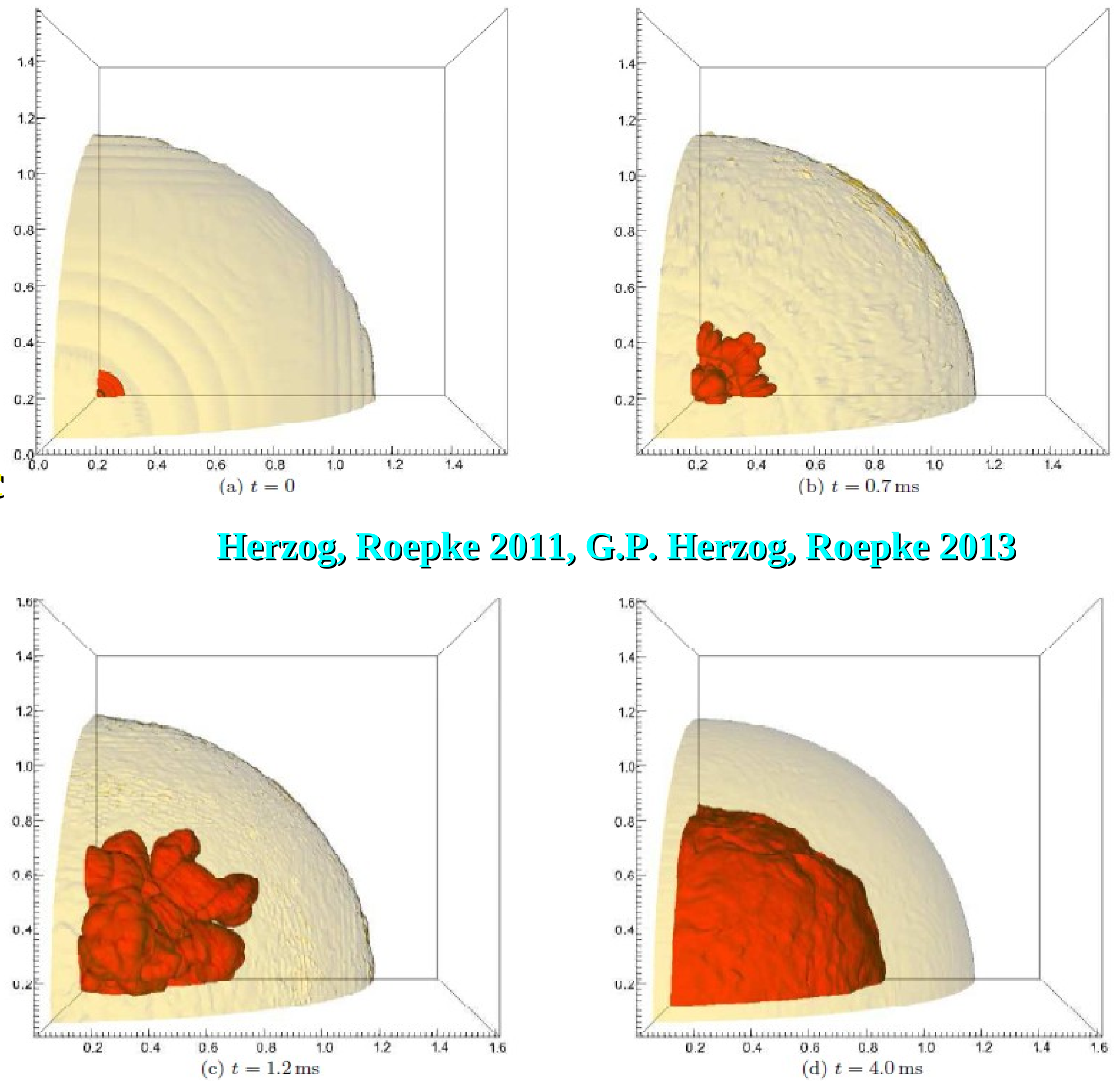


Conversion of a 1.4 M_{sun} star

-) 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)

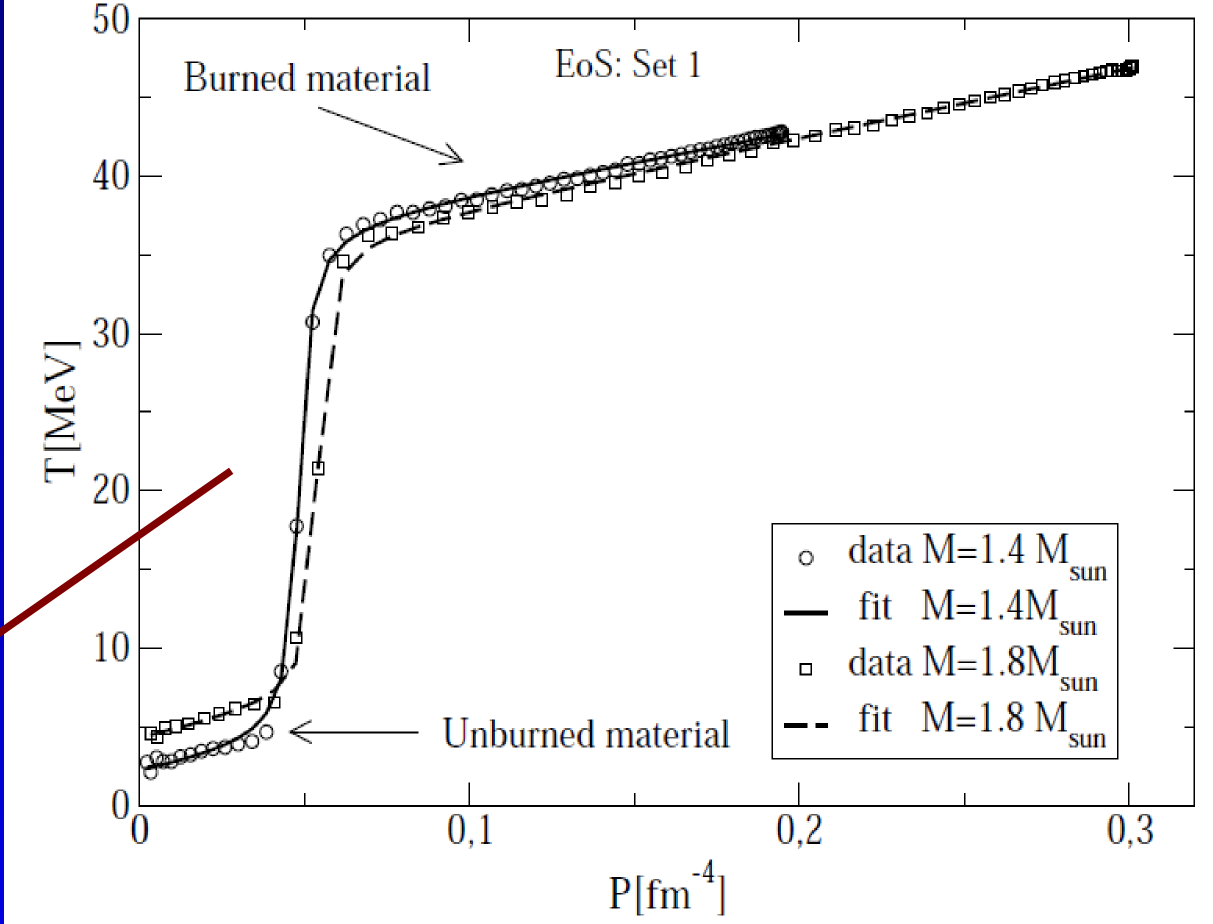


Herzog, Roepke 2011, G.P. Herzog, Roepke 2013

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.

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)

… 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

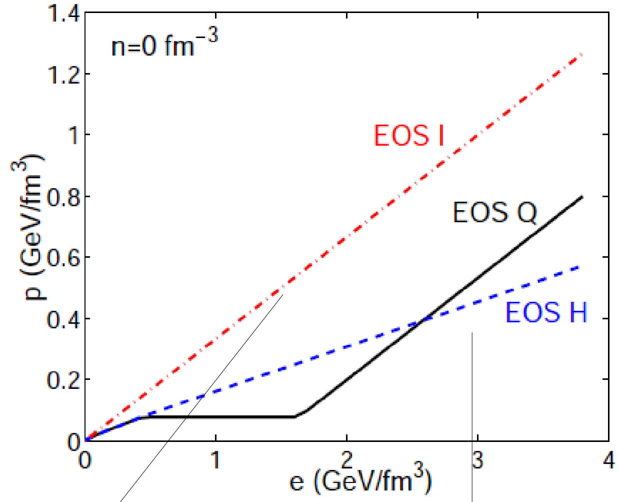


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

p=e/3 massless quarks

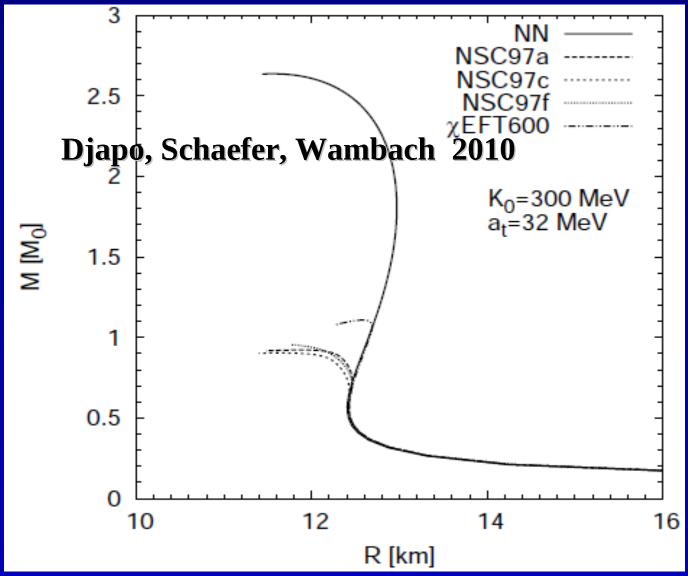
Hadron resonance gas p=e/6

… more dramatic results in microscopic calculations

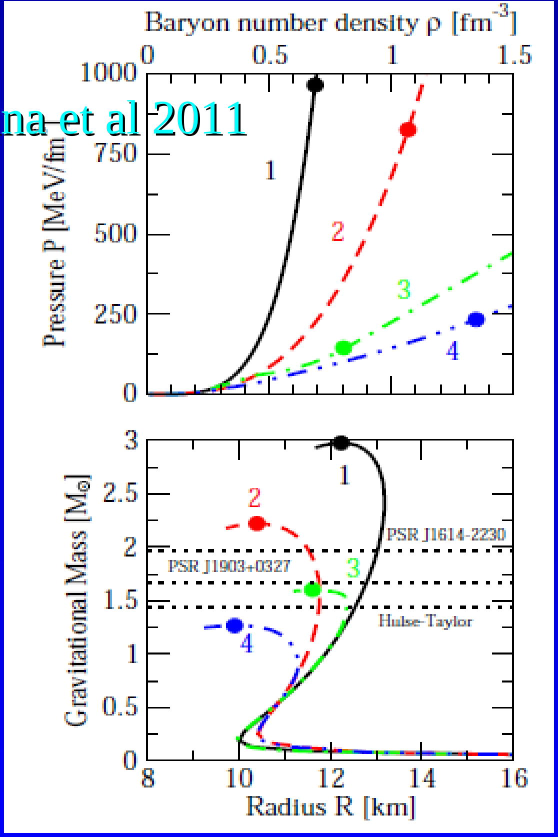
Hyperons puzzle: “*…the treatment of hyperons in neutron stars is necessary and any approach to dense matter must address this issue.*”

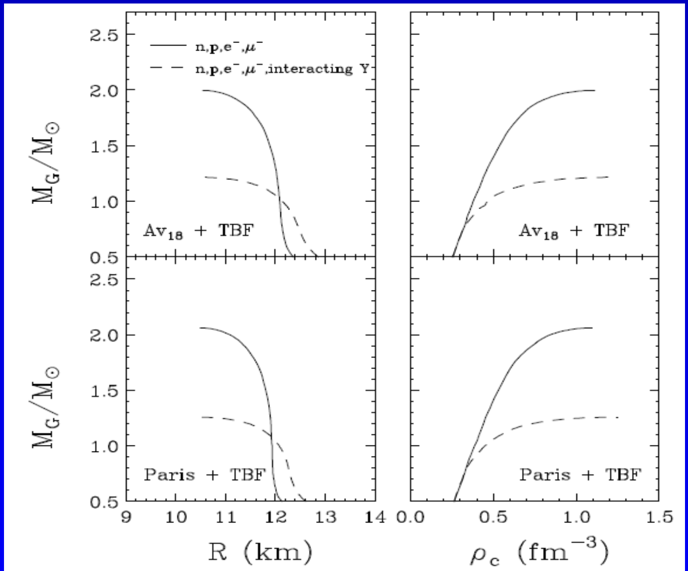
The solution is not just the “let's use only nucleons”

Djapo, Schaefer, Wambach 2010



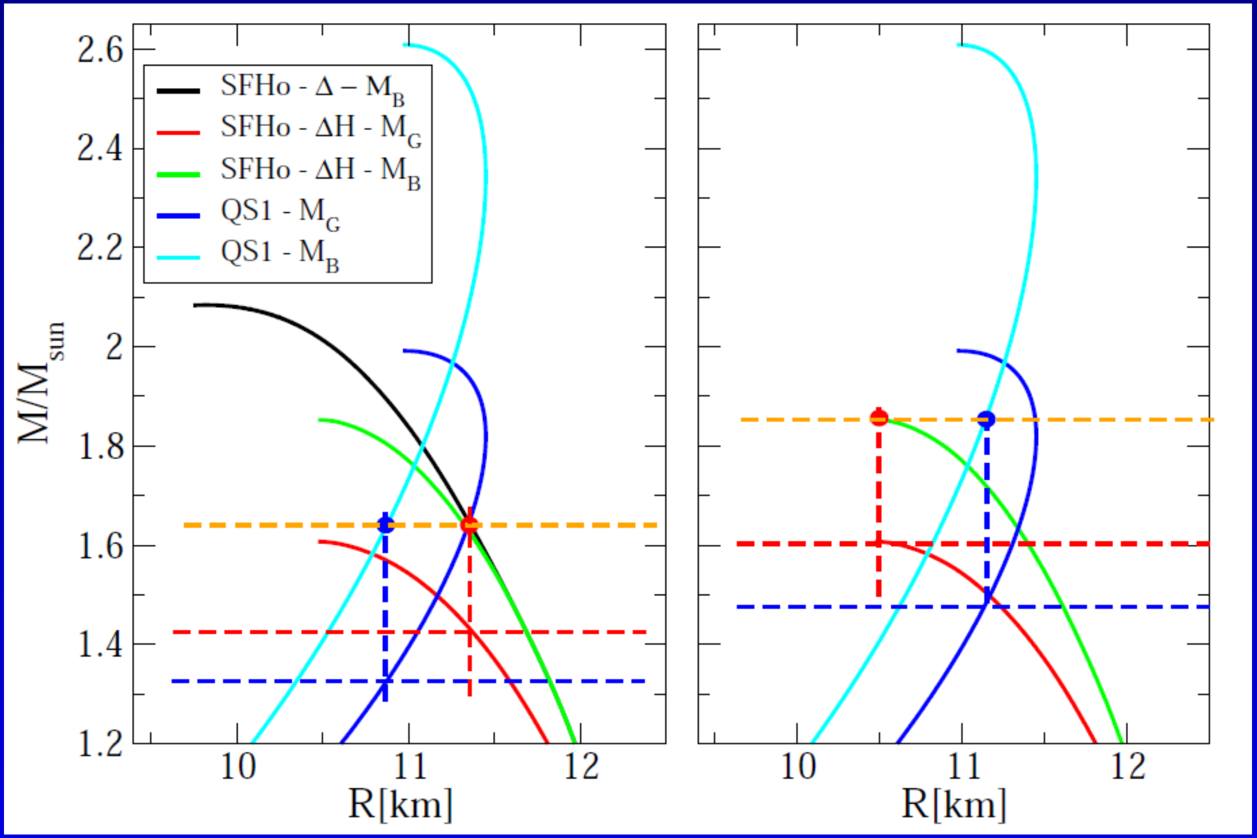
Vidana et al 2011





Baldo et al 1999

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



Temperature profiles as initial conditions for the cooling diffusion equation

Heat transport equation due to neutrino diffusion

$$\frac{\mathrm{d}}{\mathrm{dt}}\frac{\epsilon_{tot}}{n_b} + P\frac{\mathrm{d}}{\mathrm{dt}}\frac{1}{n_b} = -\frac{\Gamma}{n_b r^2 \mathrm{e}^{\Phi}}\frac{\partial}{\partial r}\left(\mathrm{e}^{2\Phi} r^2 \left(F_{\epsilon,\nu_e} + F_{\epsilon,\nu_\mu}\right)\right)$$

$$\frac{dP}{dr} = -(P+\epsilon_{tot})\frac{m+4\pi r^3 P}{r^2 - 2mr}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon_{tot}$$

$$\frac{da}{dr} = \frac{4\pi r^2 n_b}{\sqrt{1-2m/r}}$$

$$\frac{d\Phi}{dr} = \frac{m+4\pi r^3 P}{r^2 - 2mr}$$

$$F_{\epsilon,\nu_e} = -\frac{\lambda_{\epsilon,\nu_e}}{3}\frac{\partial \epsilon_{\nu_e}}{\partial r}$$

$$F_{\epsilon,\nu_\mu} = -\frac{\lambda_{\epsilon,\nu_\mu}}{3}\frac{\partial \epsilon_{\nu_\mu}}{\partial r}$$

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

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

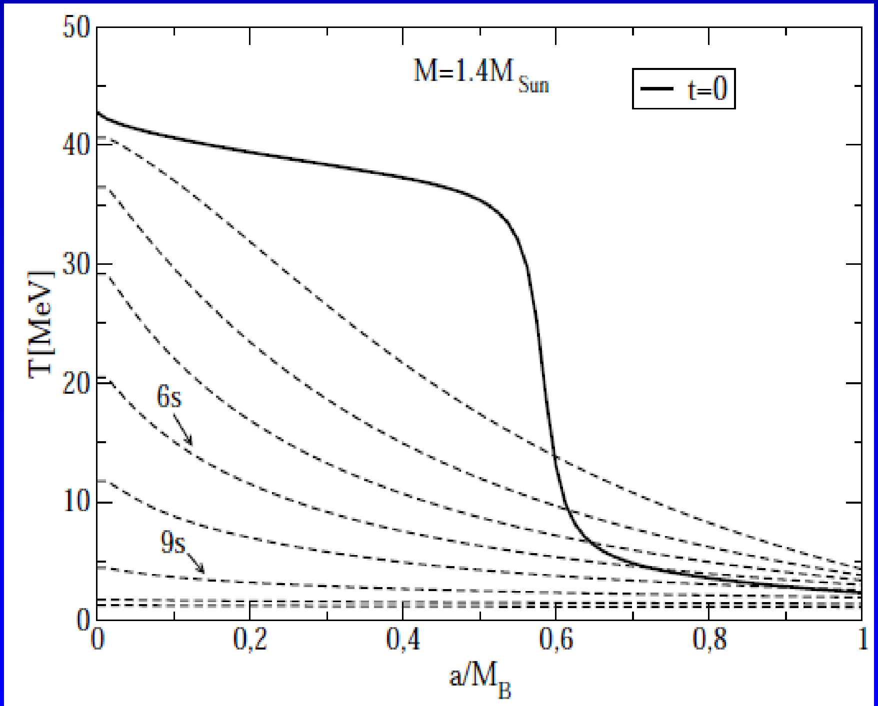
$$\frac{\sigma_S}{V} = \frac{G_F^2 E_\nu^3 \mu_i^2}{5\pi^3}$$

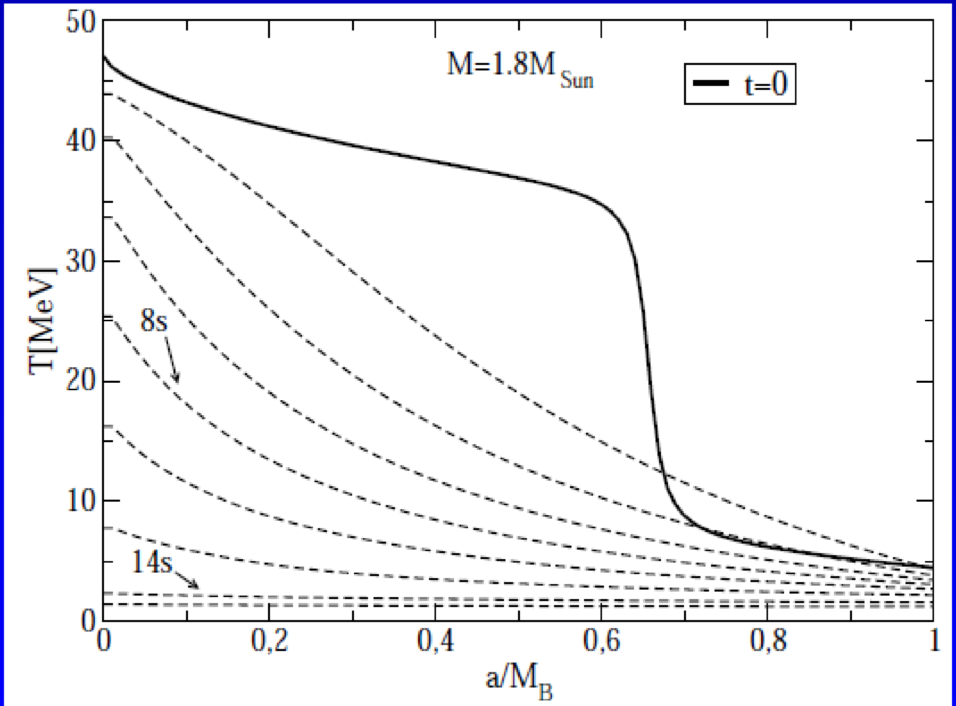
Steiner et al 2001

Expected smaller cooling times with respect to hot neutron stars

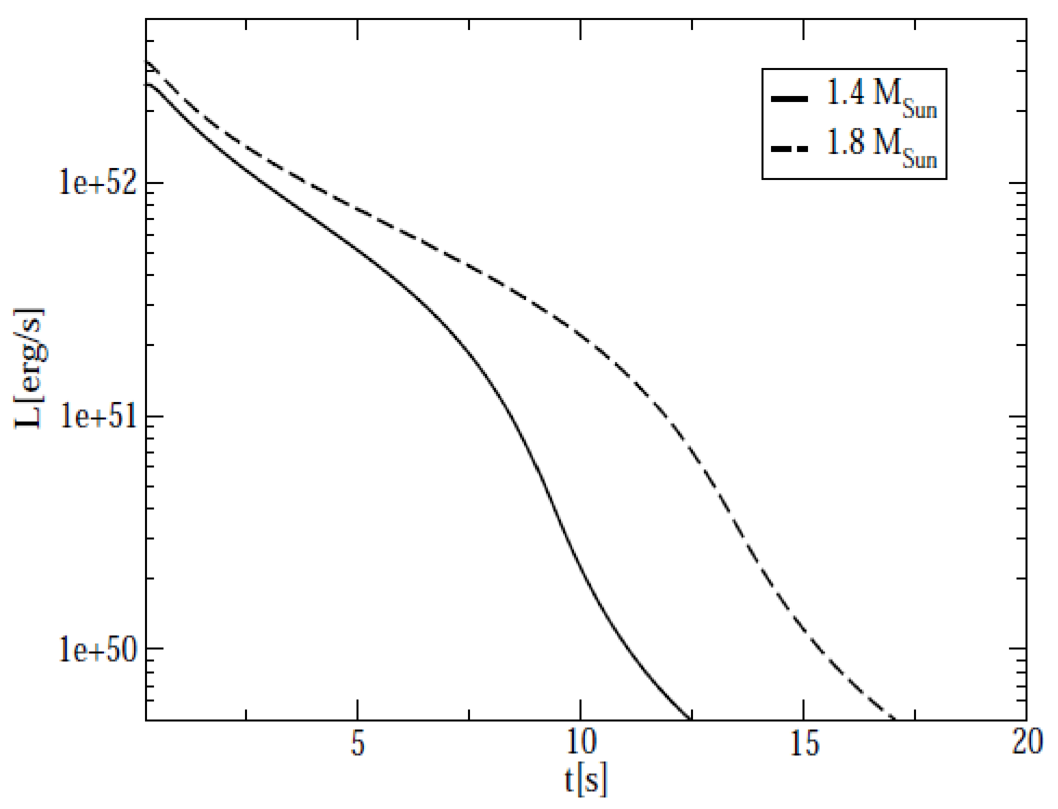
phase	process	λ(T=5 MeV)	λ(T=30 MeV)
Nuclear Matter	$\nu n \to \nu n$	200 m	1 cm
	$\nu_e n \to e^- p$	2 m	4 cm
Unpaired Quarks	$\nu q \to \nu q$	350 m	1.6 m
	$\nu d \to e^- u$	120 m	4 m
CFL	λ_{3B}	100 m	70 cm
	$\nu \phi \to \nu \phi$	>10 km	4 m

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 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]

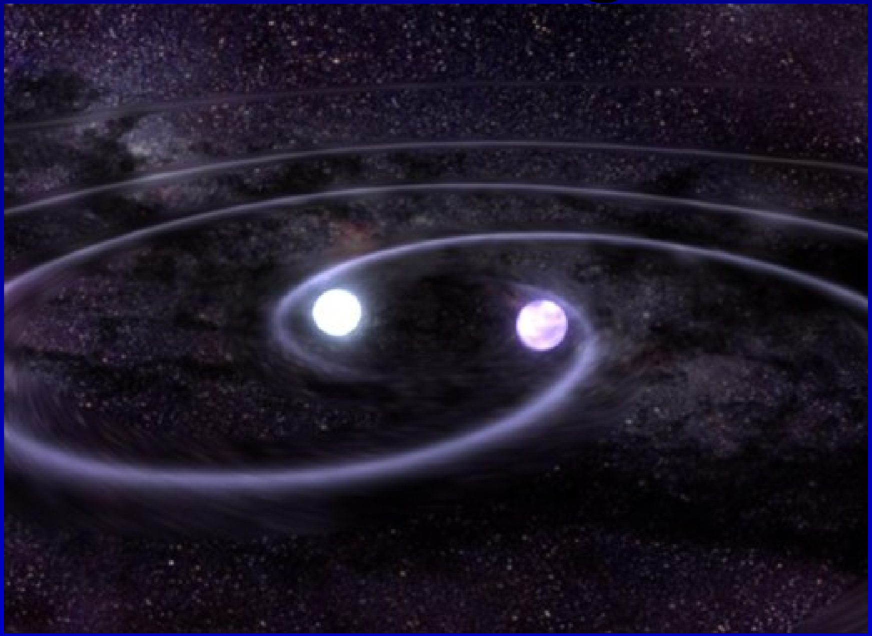
Draft version January 17, 2012

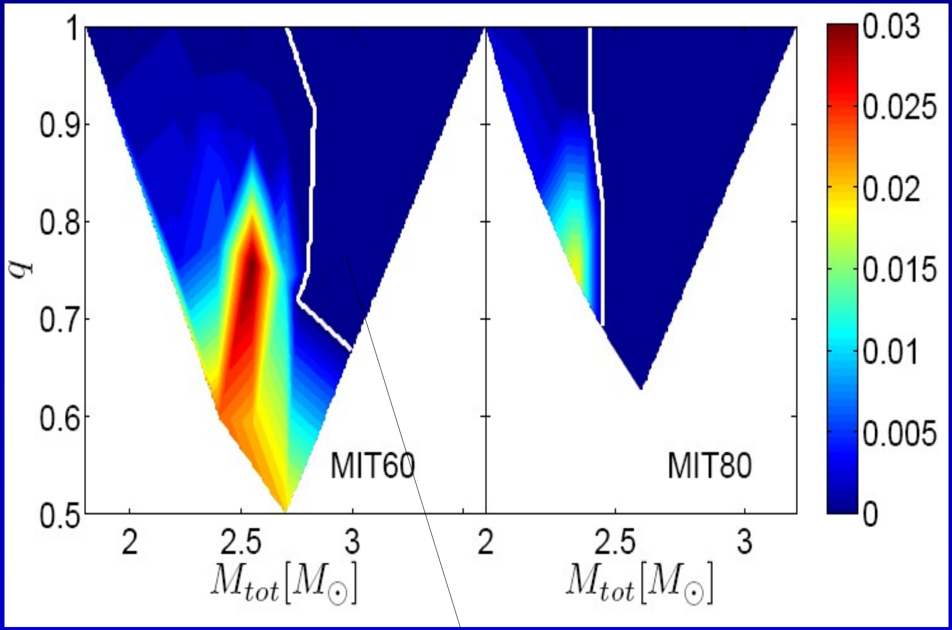
ABSTRACT

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

Are all compact stars strange?: Merger of strange stars





MIT60: 8 10^{-5} Msun, 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)

Prompt collapse: in our scenario quark stars have masses larger than ~ 1.5 M_{sun}, no strangelets emitted.

Hyperons in compact stars

Few experimental data from hypernuclei: potential depths of Λ, Σ, Ξ allow to fix three parameters (usually the coupling with a scalar meson).

Within RMF:

(see Weissenborn, Chatterjee, Schaffner-Bielich 2012)

$$\mathcal{L} = \sum_B \bar{\Psi}_B \left(i\gamma_\mu \partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - g_{\rho B}\gamma_\mu \mathbf{t}_B \cdot \boldsymbol{\rho}^\mu \right) \Psi_B$$
$$+ \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right) - U(\sigma) + U(\omega)$$
$$- \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu} \cdot \boldsymbol{\rho}^{\mu\nu} + \frac{1}{2} m_\rho^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu .$$

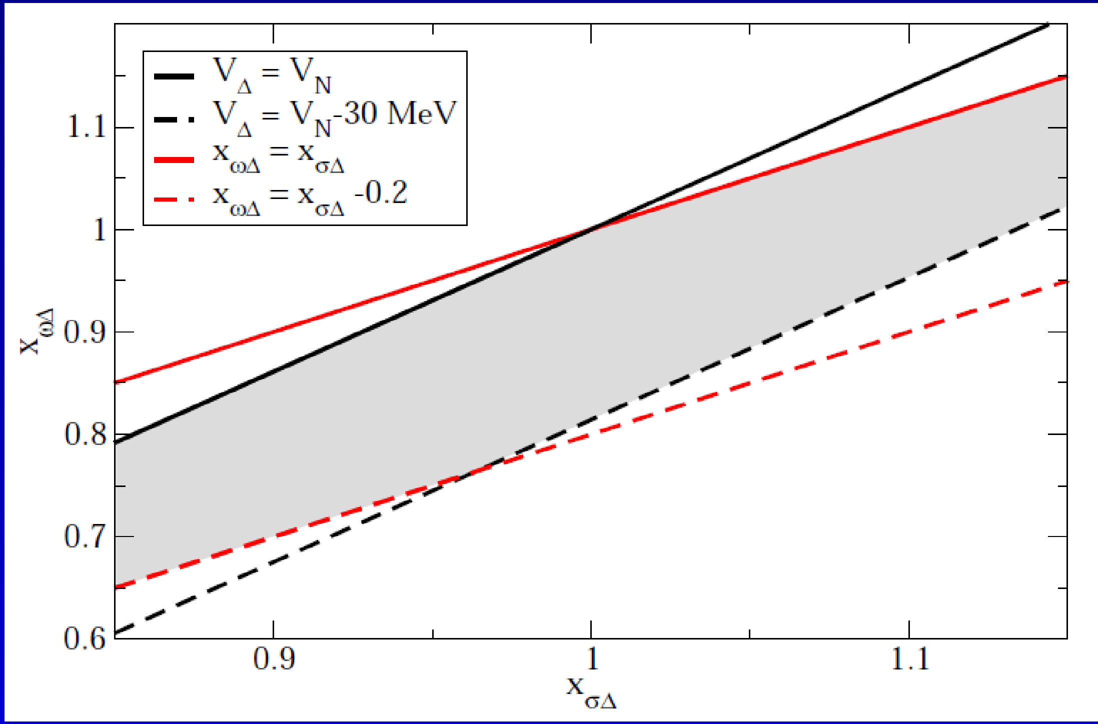
$$\mathcal{L}_{YY} = \sum_B \bar{\Psi}_B \left(g_{\sigma^* B}\sigma^* - g_{\phi B}\gamma_\mu \phi^\mu \right) \Psi_B$$
$$+ \frac{1}{2}\left(\partial_\mu \sigma^* \partial^\mu \sigma^* - m_{\sigma^*}^2 \sigma^{*2} \right)$$
$$- \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu .$$

Additional YY interaction

$$\frac{1}{3} g_{\omega N} = \frac{1}{2} g_{\omega \Lambda} = \frac{1}{2} g_{\omega \Sigma} = g_{\omega \Xi},$$
$$g_{\rho N} = \frac{1}{2} g_{\rho \Sigma} = g_{\rho \Xi},$$
$$g_{\rho \Lambda} = 0,$$
$$2 g_{\phi \Lambda} = 2 g_{\phi \Sigma} = g_{\phi \Xi} = -\frac{2\sqrt{2}}{3} g_{\omega N}.$$

Couplings with vector mesons from flavor symmetry

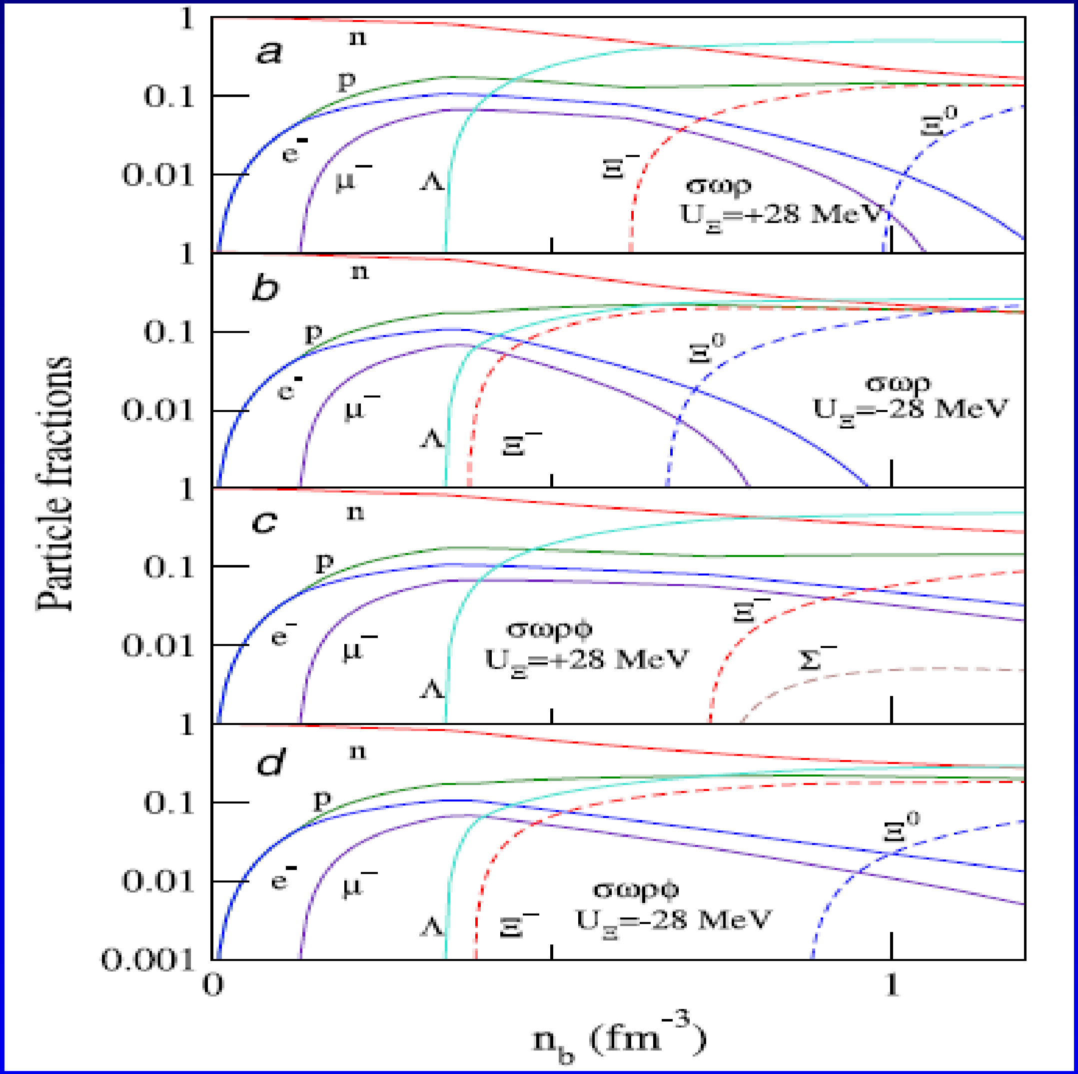
This allows to constrain the free parameters within the RMF model. Notice: coupling with ω mesons suppressed wrt the coupling with the σ meson. The coupling(ratio) with the ρ meson fixed to 1.



Implications for compact stars ?

Particle's fractions

Beta stable matter (equilibrium with respect to weak interaction+charge neutrality): large isospin asymmetry and large strangeness , very different from the nuclear matter produced in heavy ions collisions



Notice: hyperons appear at 2-3 times saturation density

The appearance of hyperons sizably softens the equation of state: reduced maximum mass

Introducing the ϕ meson to obtain YY repulsion allows to be marginally consistent with the astrophysical data.

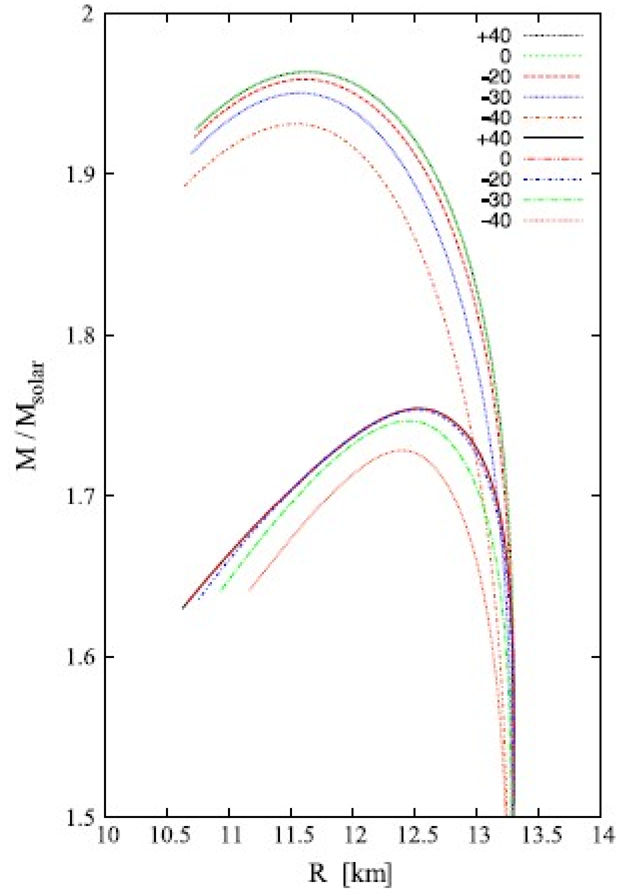
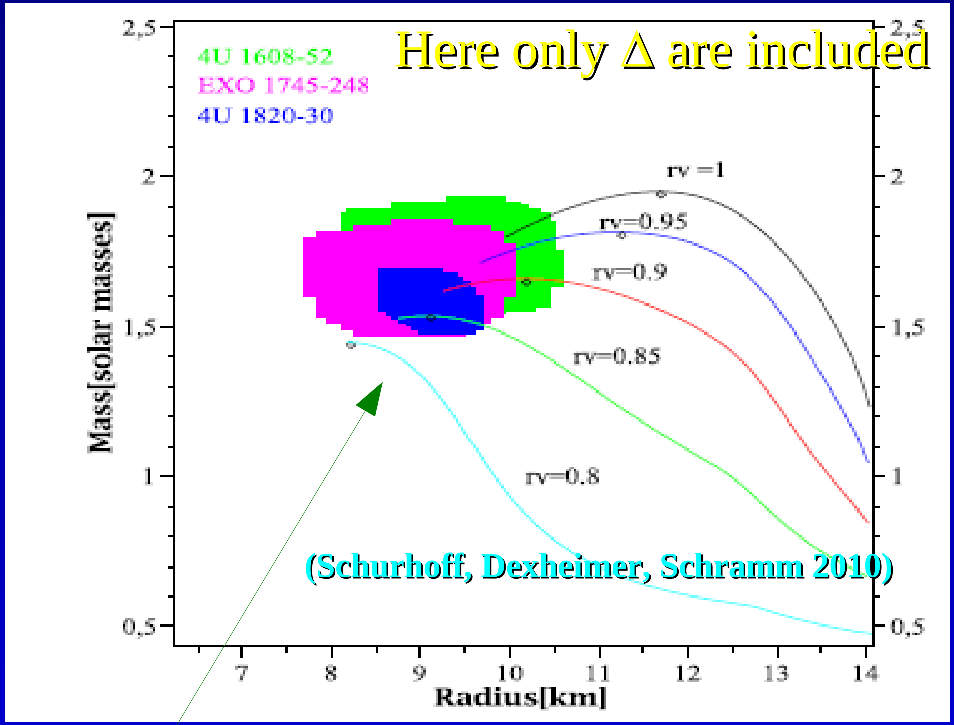


Fig. 2. Mass radius relations for neutron stars obtained with the EoS from Fig. 1. The variation of $U_{\Sigma}^{(N)}$ in "model $\sigma\omega\rho$" cannot account for the observed neutron star mass limit (lower branch), unless the ϕ meson is included in the model (upper branch).

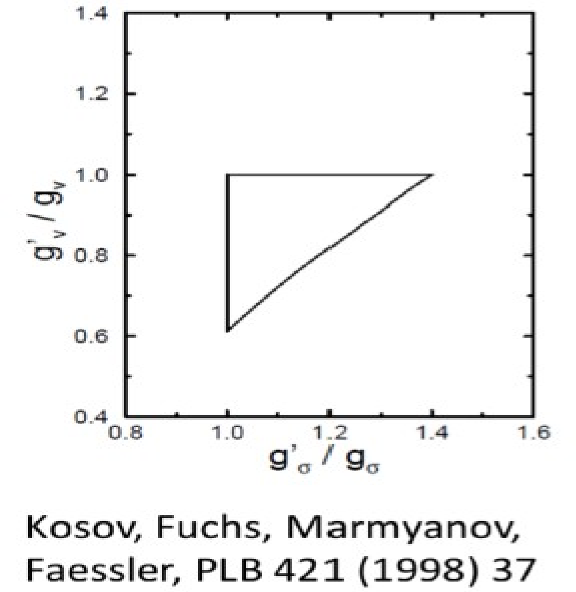
… but: σ^* (to be interpreted as the f0(980)) has not been included. Introducing this additional interaction would again reduce the maximum mass

What about Δ?

Similar effects: softening of the equation of state. Just small changes of the couplings with vector mesons sizably decrease the maximum mass

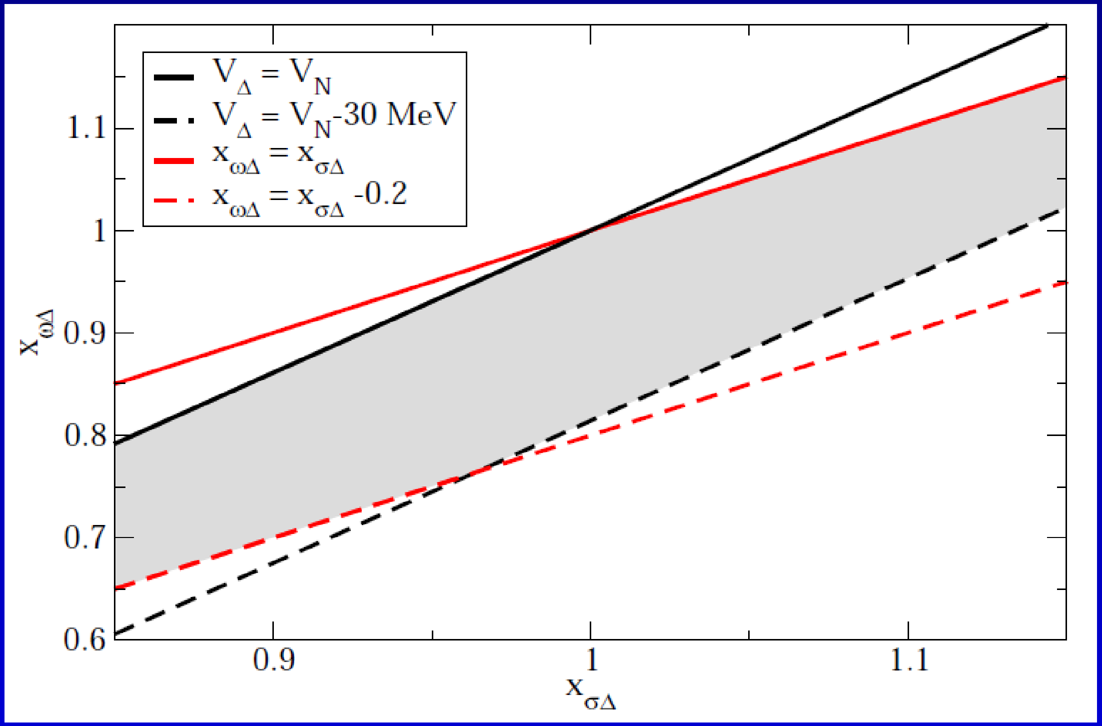


Notice: very small radii



Some constraints on the couplings with mesons from nuclear matter properties and QCD sum rules

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 ?

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.

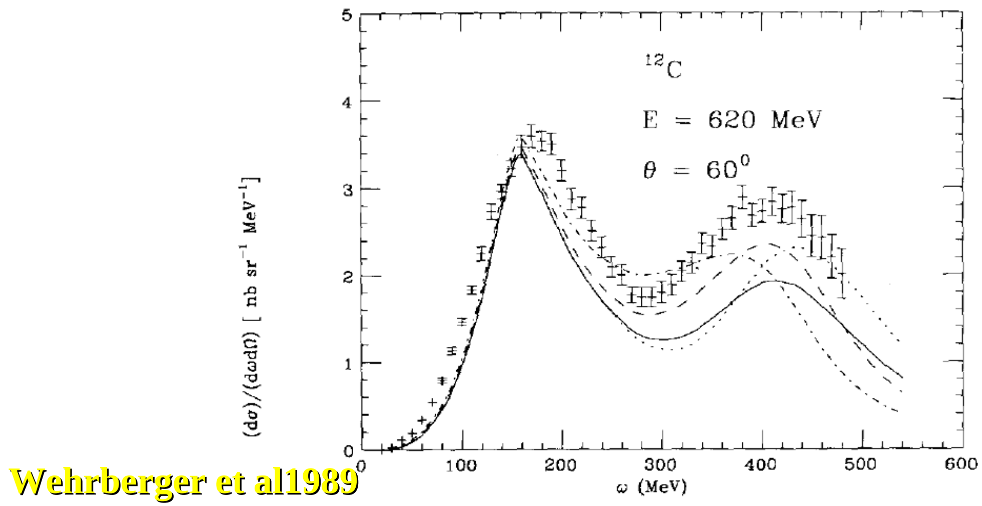


Fig. 13. Cross section for electron scattering on ^{12}C at incident electron energy $E = 620$ MeV and scattering angle $\theta = 60°$ as a function of energy transfer ω for standard nucleon and different Δ-couplings. The lines are the results for the sum of the contribution from nucleon knockout and 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]).

Phenomenological potentials:

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

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

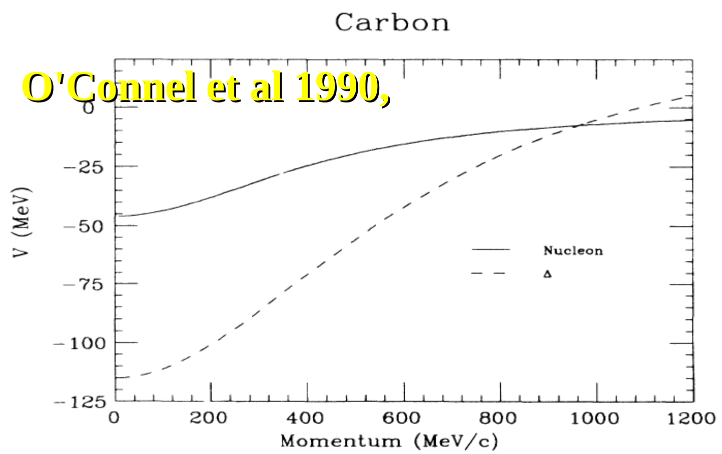


FIG. 4. Phenomenological nucleon-nucleus, solid line, and Δ nucleus, dashed line, momentum-dependent potentials for C.