Dense nuclear matter in neutron stars

Giuseppe Pagliara

Dipartimento di Fisica e Scienze della Terra, Universita' di Ferrara & INFN Ferrara, Italy

New Frontiers in Physics III & FAIR workshop, Kolymbari, Crete, 28/07/2014

Outline

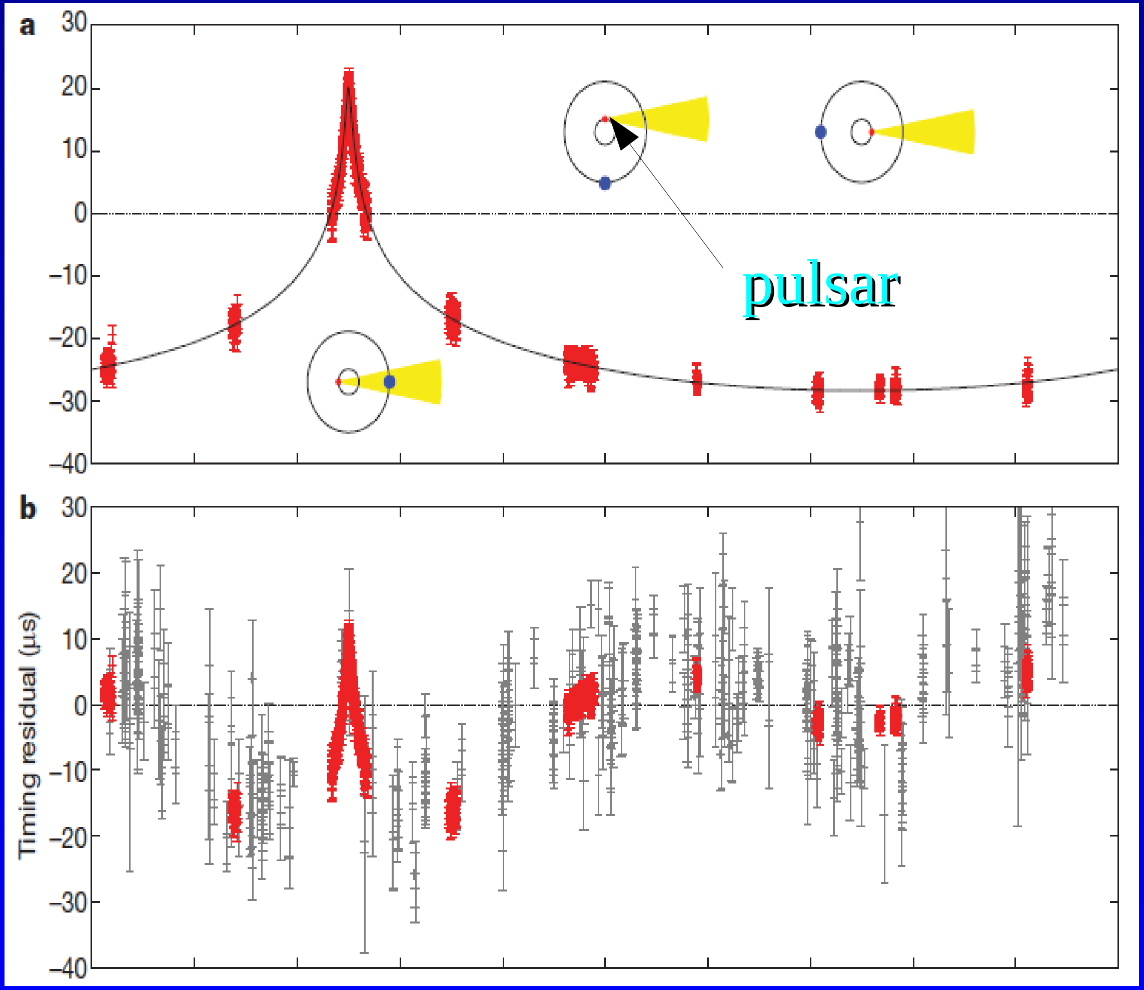
- -) Precise mass measurements: existence of $2M_{sun}$ stars
- -) Implications for the equation of state: nucleons, Δ, hyperons, “deconfined” quarks ?
- -) radii mesurements: existence of stars with R <10km (large uncertainties)
- -) Two families of compact stars ? Connection with (double) explosions SN and GRB events

A milestone for the physics of neutron stars: PSR J1614-2230, 1.97±0.04 M_{sun} star

(Demorest et al. Nature 2010)

Shapiro delay: GR effect of increasing the light travel time through the curved space-time near a massive body.

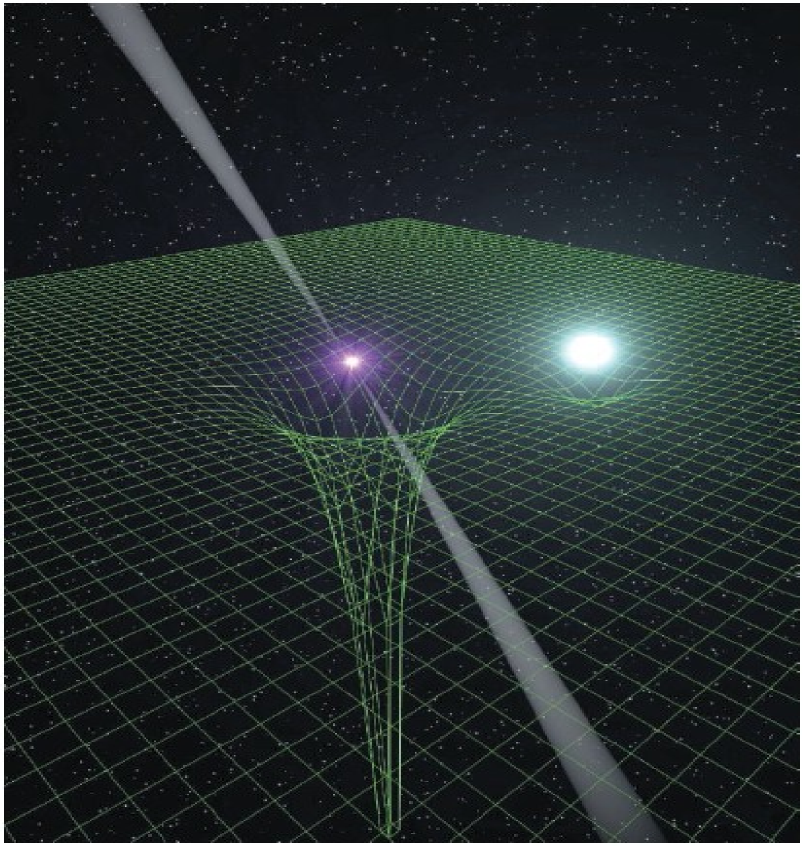
How was it possible? Great observational and data-analysis set-up...
Luck: quite massive white dwarf companion 0.5 M_{sun} and the orbital plane almost edge-on.



… recently a even higher mass $2.01 \pm 0.04\ M_{sun}$ (Antoniadis et al Science 2013)

Pulsar timing and spectra of the white dwarf companion allows to measure the mass of the two stellar objects.

Moreover, the decrease in the orbital period is perfectly in agreement with gravitational waves emission.

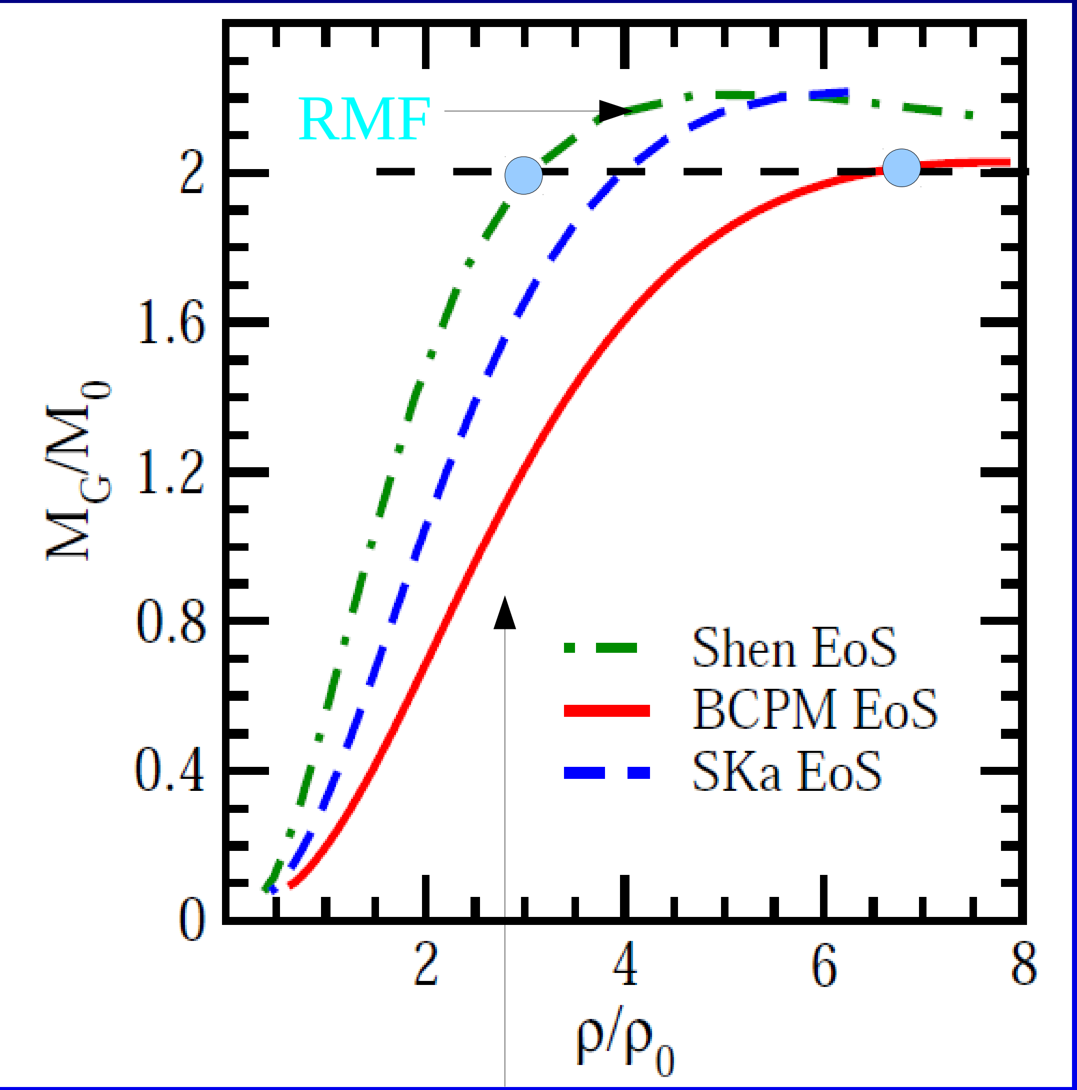


Artist's impression of the PSR J0348+0432 system. The compact pulsar (with beams of radio emission) produces a strong distortion of spacetime (illustrated by the green mesh). Conversely, spacetime around its white dwarf companion (in light blue) is substantially less curved. According to relativistic theories of gravity, the binary system is subject to energy loss by gravitational waves.

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

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)

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

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

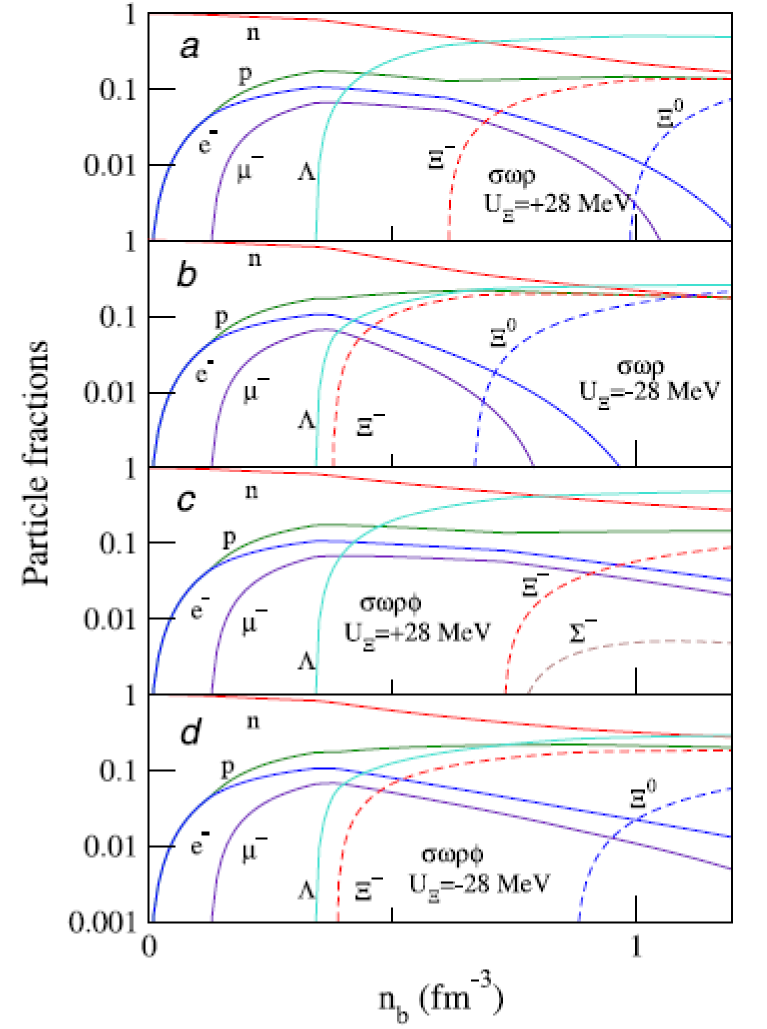
Additional YY interaction

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

Couplings with vector mesons from flavor symmetry

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 phi meson to obtain YY repulsion allows to be marginally consistent the astrophysical data.

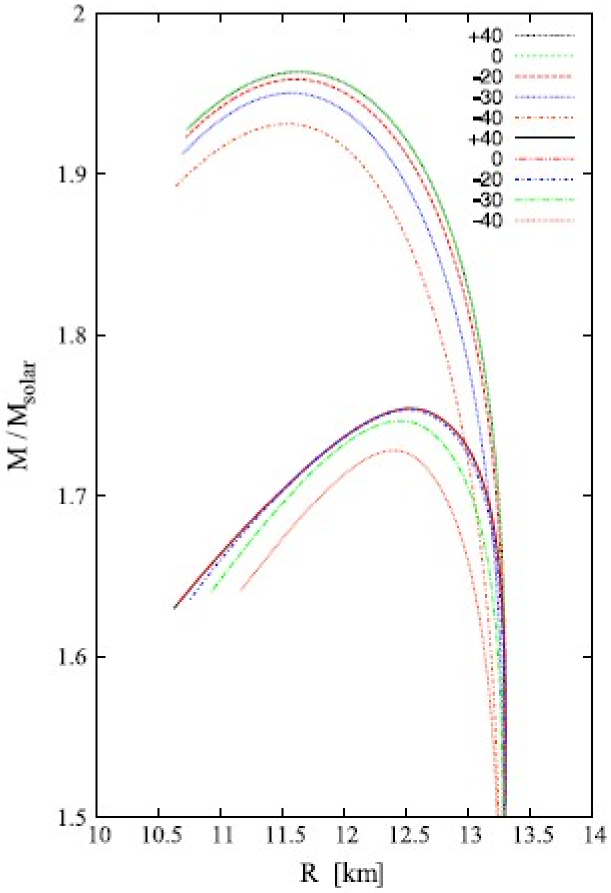


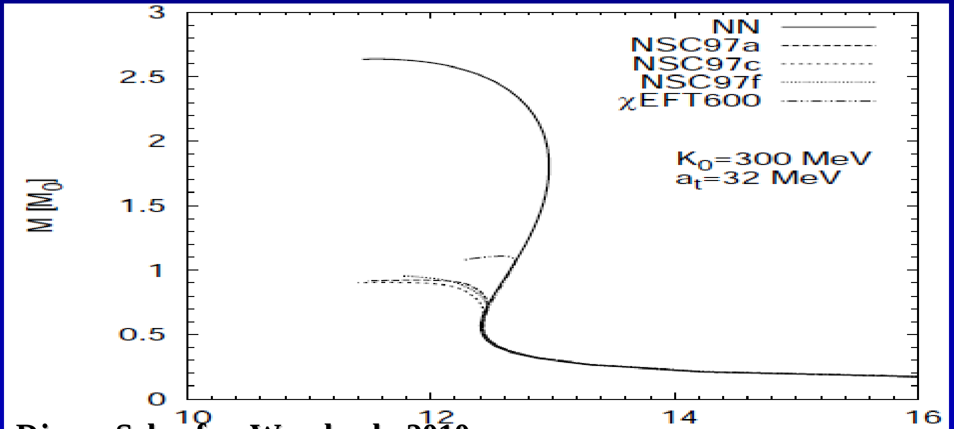
Fig. 2. Mass radius relations for neutron stars obtained with the EoS from Fig. 1. The variation of $U_\Sigma^{(N)}$ in “model $\sigma\omega\rho$” cannot account for the observed neutron star mass limit (lower branch), unless the ϕ meson is included in the model (upper branch).

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

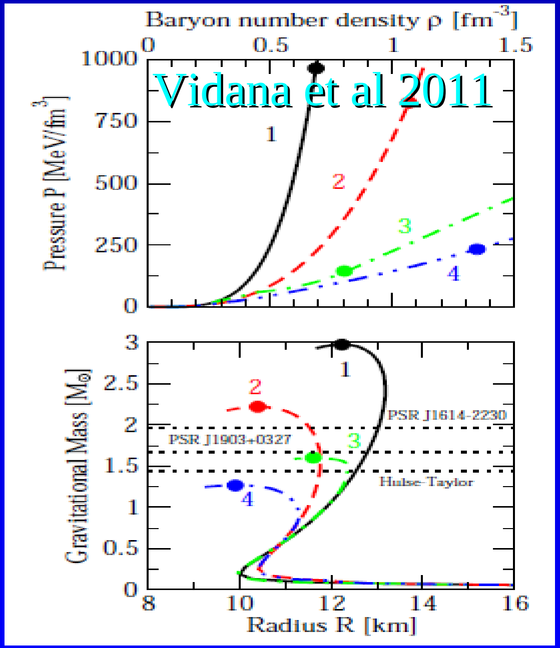
… more dramatic results in microscopic calculations

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



What about Δ?

Among the four isobars, the Δ^- is likely to appear first in beta-stable matter because it is charge-favored:

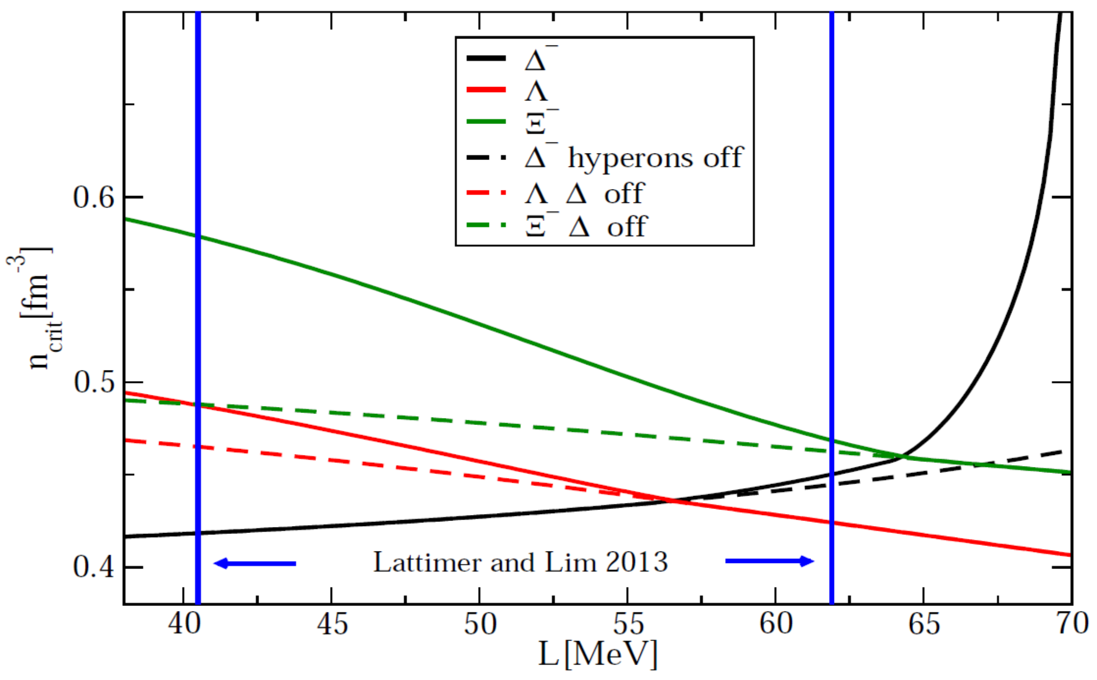
$$\mu_i = \mu_B + c_i\, \mu_C$$

But, it is isospin unfavored:

$$\mu_i \geq m_i - g_{\sigma i}\sigma + g_{\omega i}\omega + t_{3i} g_{\rho i}\rho$$

Indeed, in old calculations (see e.g. Glendenning 1985), no deltas are formed in neutron star matter. This is due to the large value of the symmetry energy at densities above saturation.

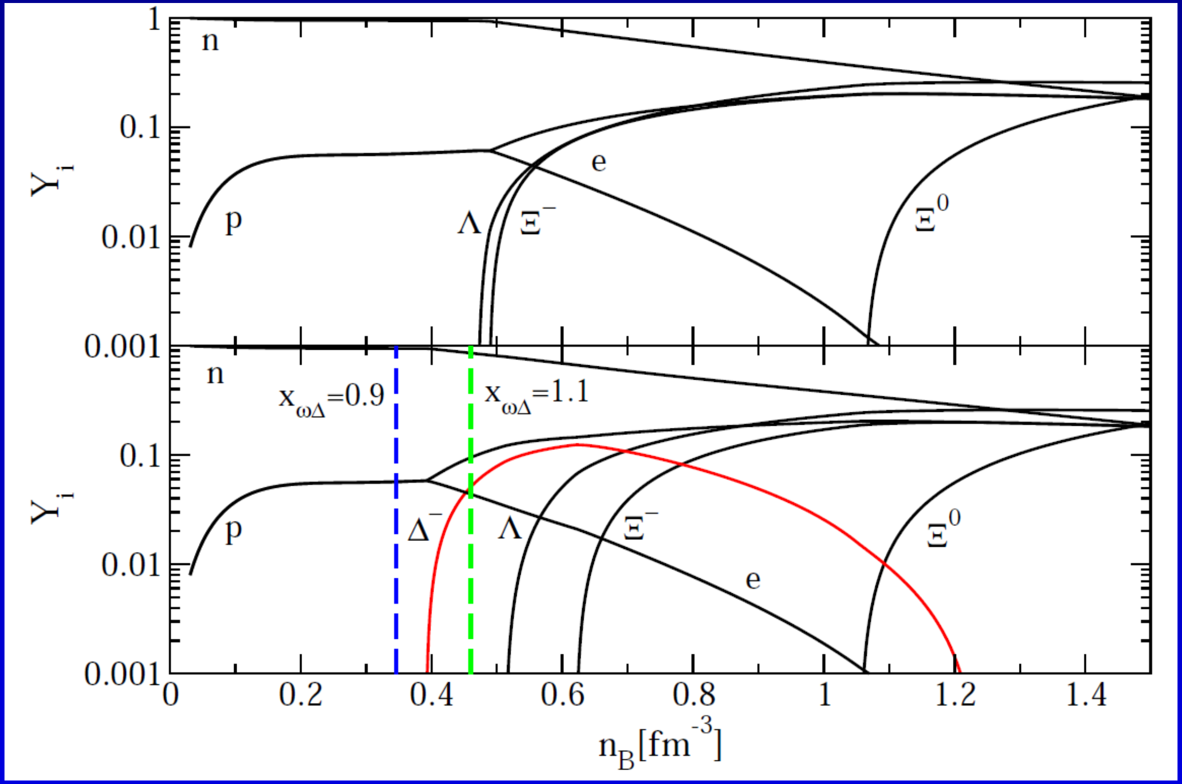
Investigating the role of the symmetry energy on the formation of the deltas by use of the density derivative of the symmetry energy L, within RMF models (Drago, Lavagno, G.P., Pigato 2014)



Glendenning's results

Punchline: recent experimental limits on L imply an early appearane of deltas in beta stable matter, they must be included when computing the equation of state of neutron star matter!!

Recent RMF model parametrization by Steiner, Fischer, Hempel (2013), new experimental information on the density dependence of the symmetry energy implemented.



The critical densities for the deltas depend on their couplings with the mesons, the most natural choice would be to take them equal to the couplings of the nucleons with the same mesons. But, do we have any experimental information on these couplings??

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

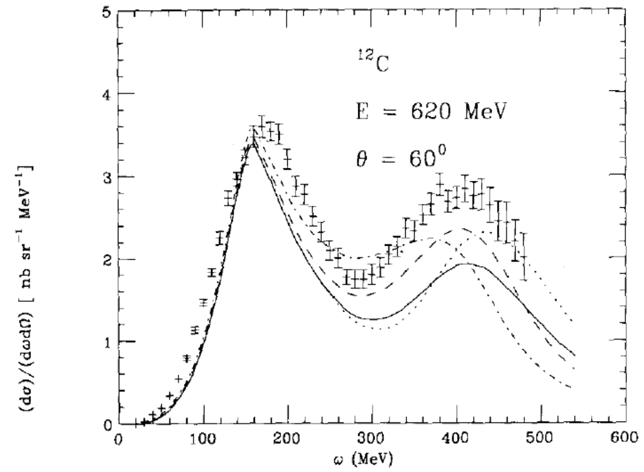
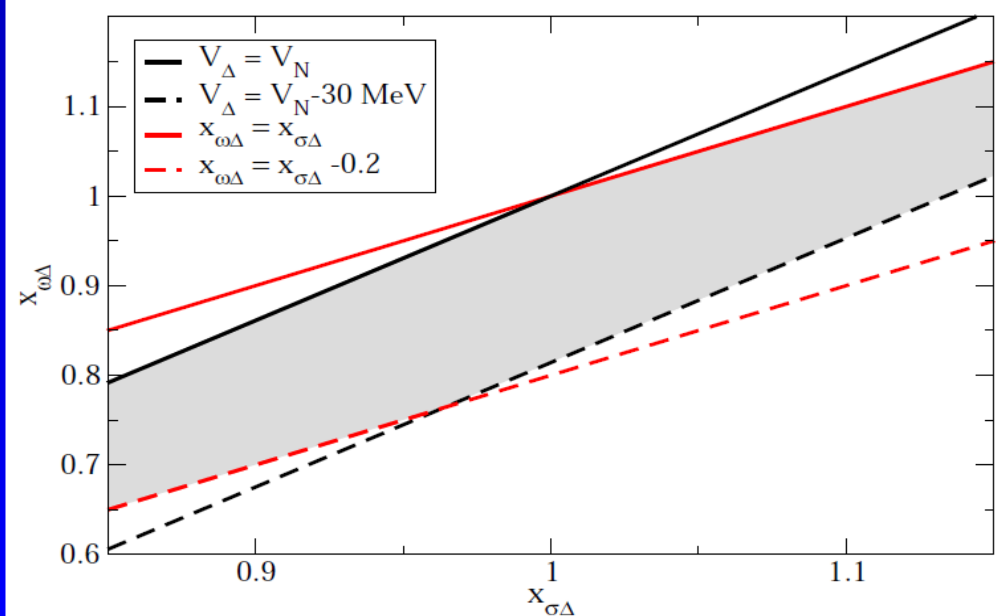
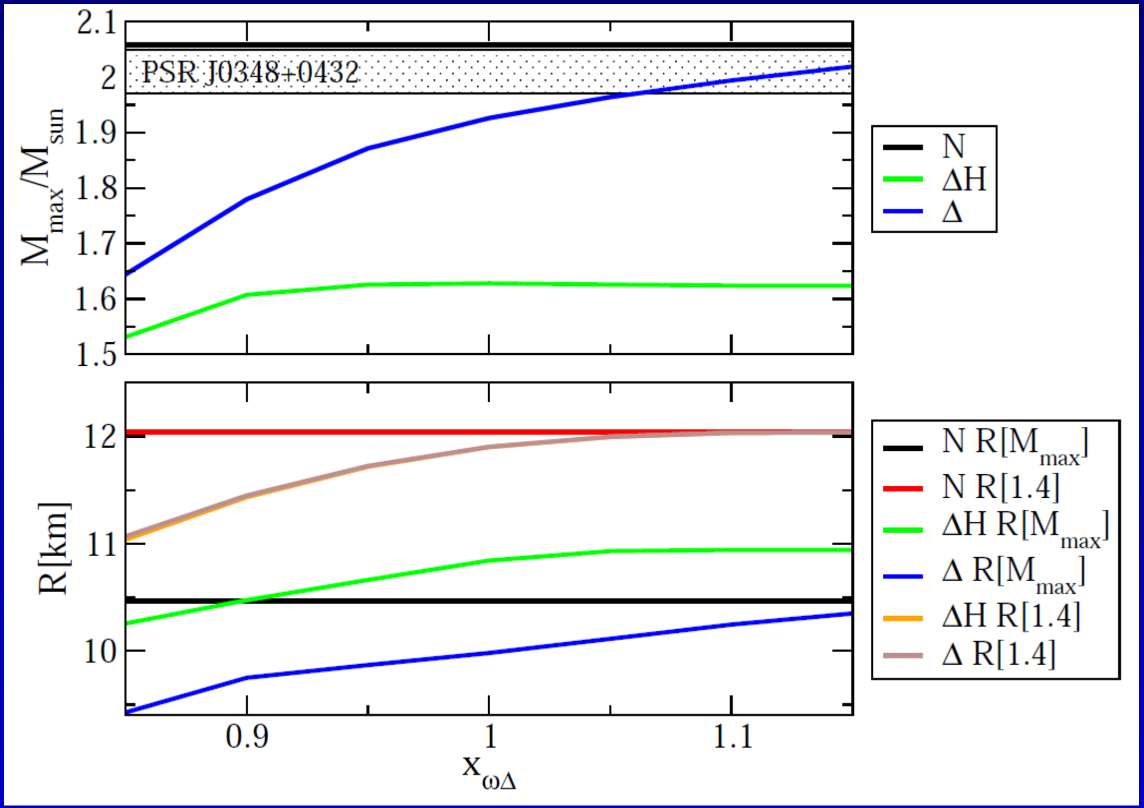


Fig. 13. Cross section for electron scattering on ^{12}C at incident electron energy $E = 620$ MeV and scattering angle $\theta = 60°$ as a function of energy transfer ω for standard nucleon and different Δ-couplings. The lines are the results for the sum of the contribution from nucleon knockout and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

This allows to constrain the free parameters within the RMF model. Notice: coupling with ω mesons suppressed.

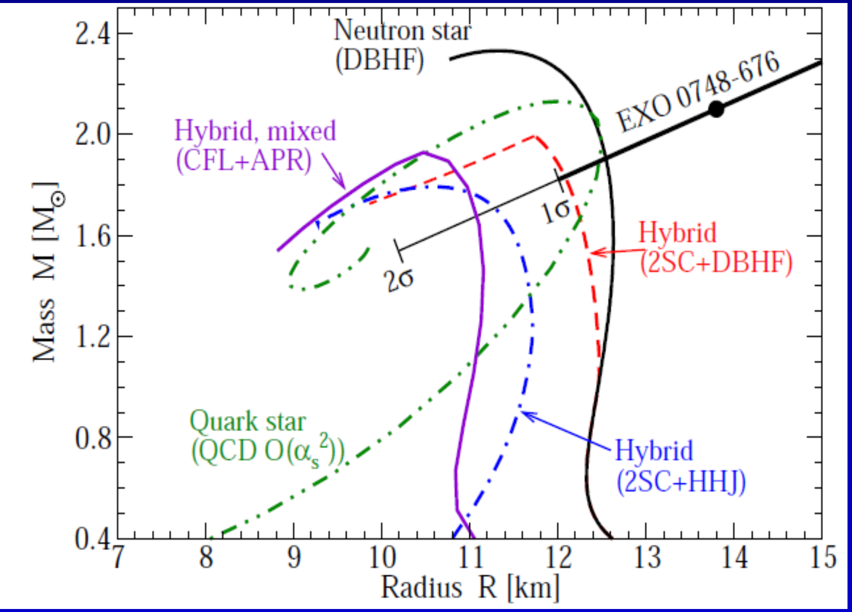


Maximum mass and radii: the maximum mass is significantly smaller than the measured ones. Also, very compact stellar configurations are possible.

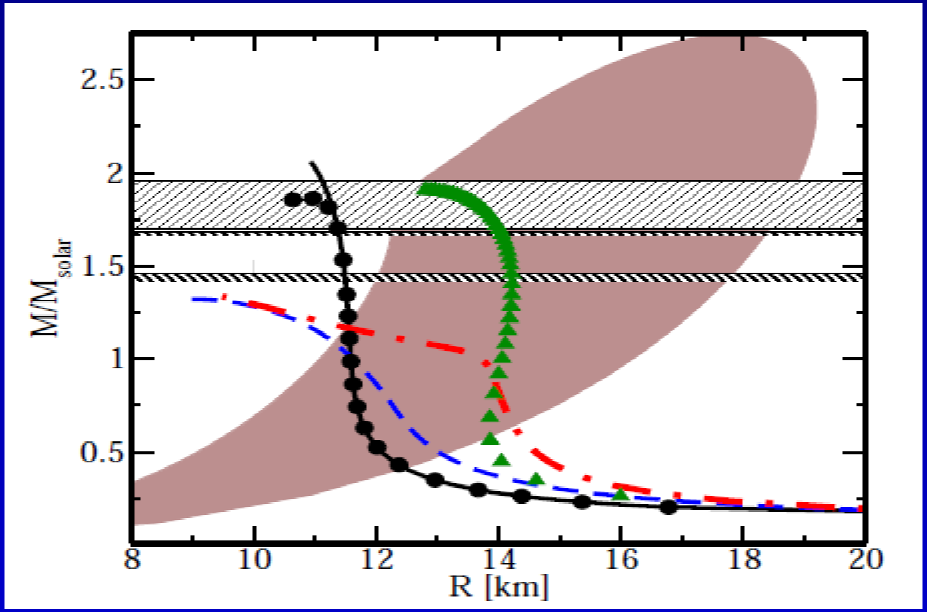


Punchline/?: beside the "hyperon puzzle" is there also a "delta isobars puzzle"?

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!!

… 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

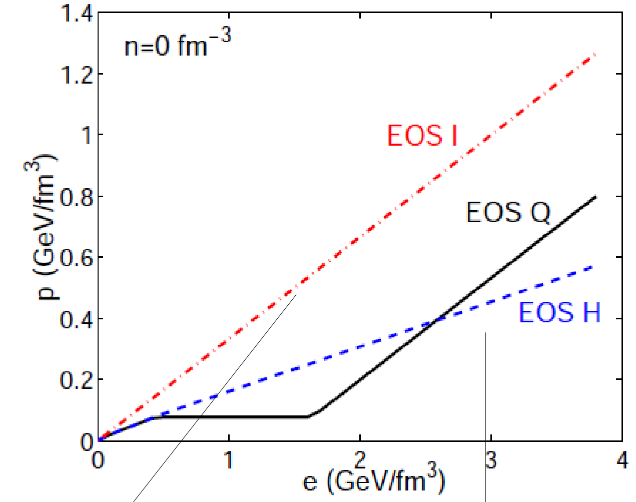
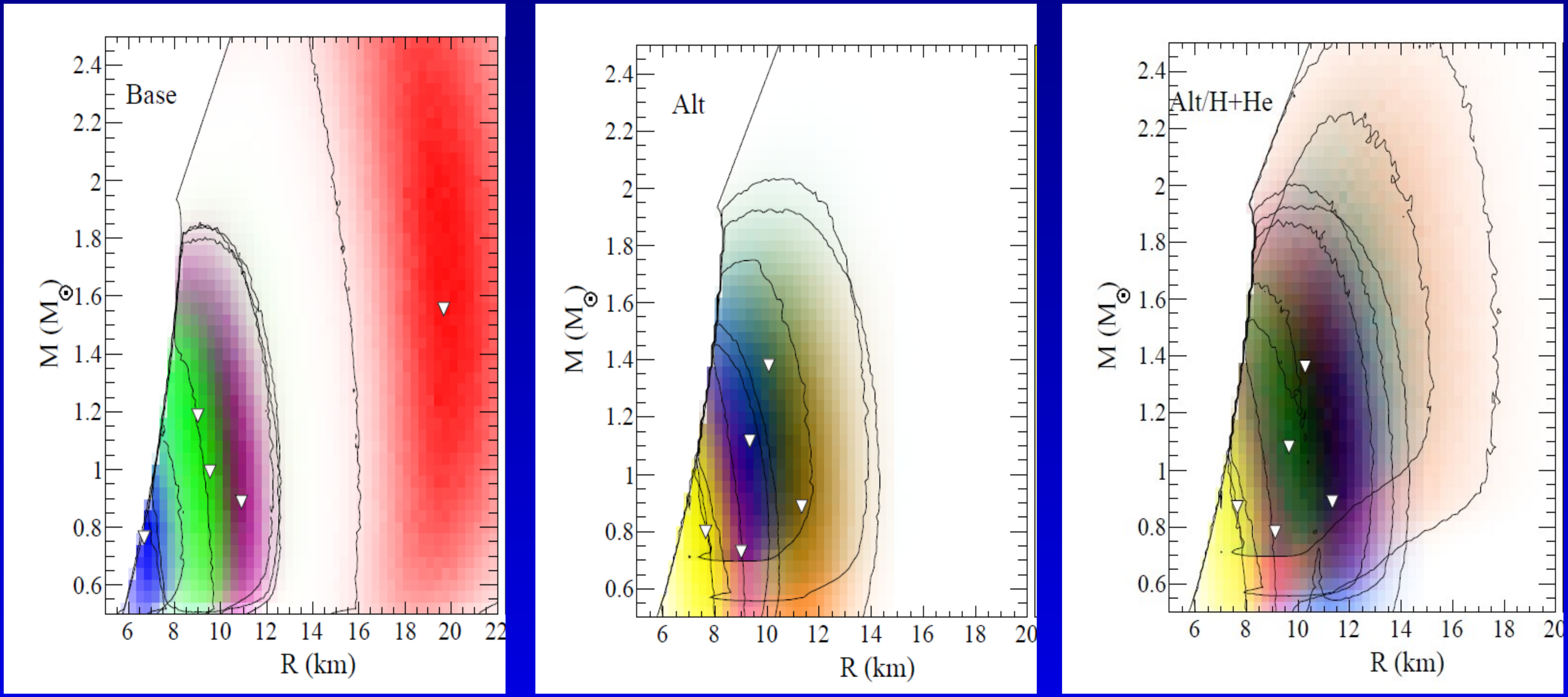


Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

p=e/3 massless quarks

Hadron resonance gas

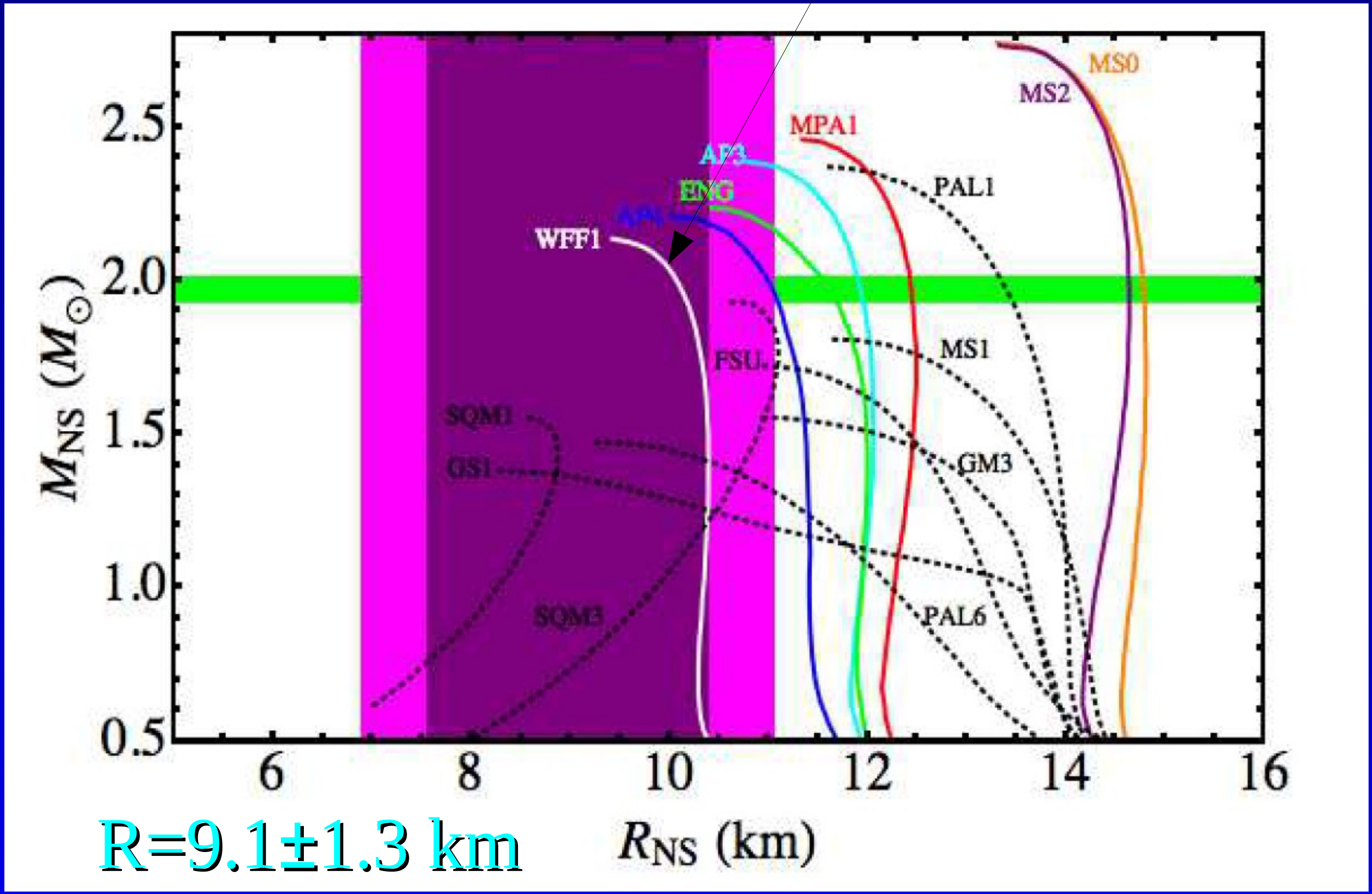
Recent radii measurements



Guillot et al. ApJ772(2013)7

Lattimer and Steiner 1305.3242

Nice, but just nucleons & violates causality

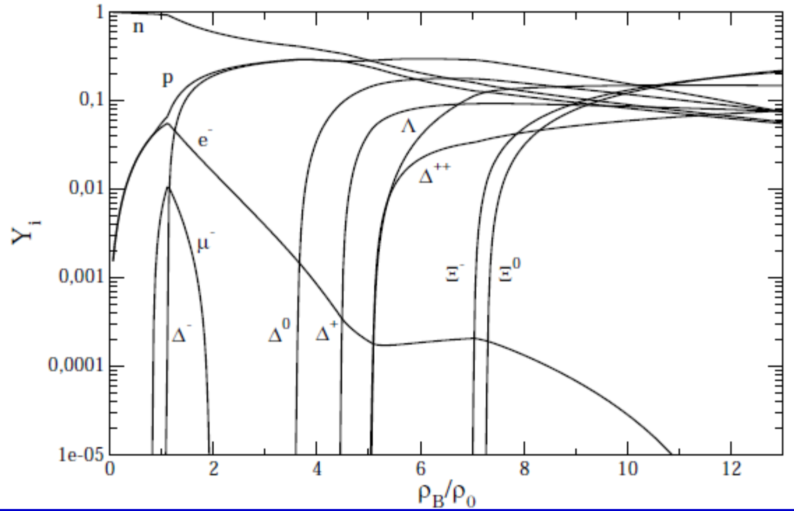


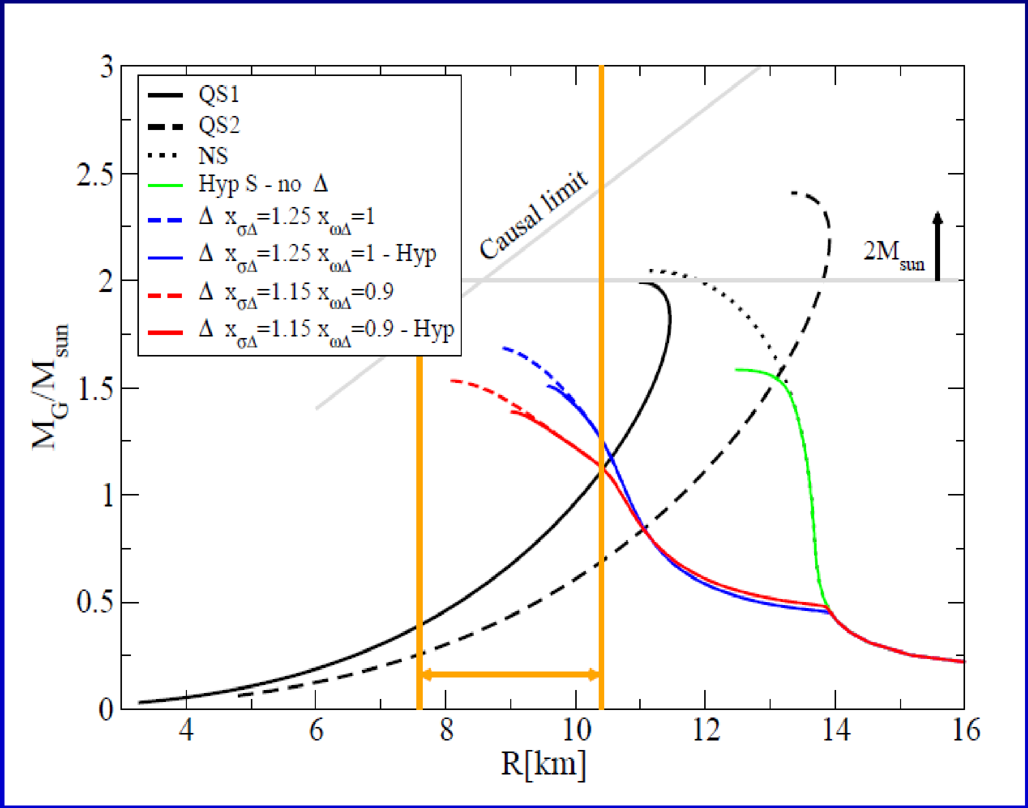
Two apparently contraddicting results: high mass → stiff equation of state

small radii → soft equation of state

Drago, Lavagno, G.P. 2013

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





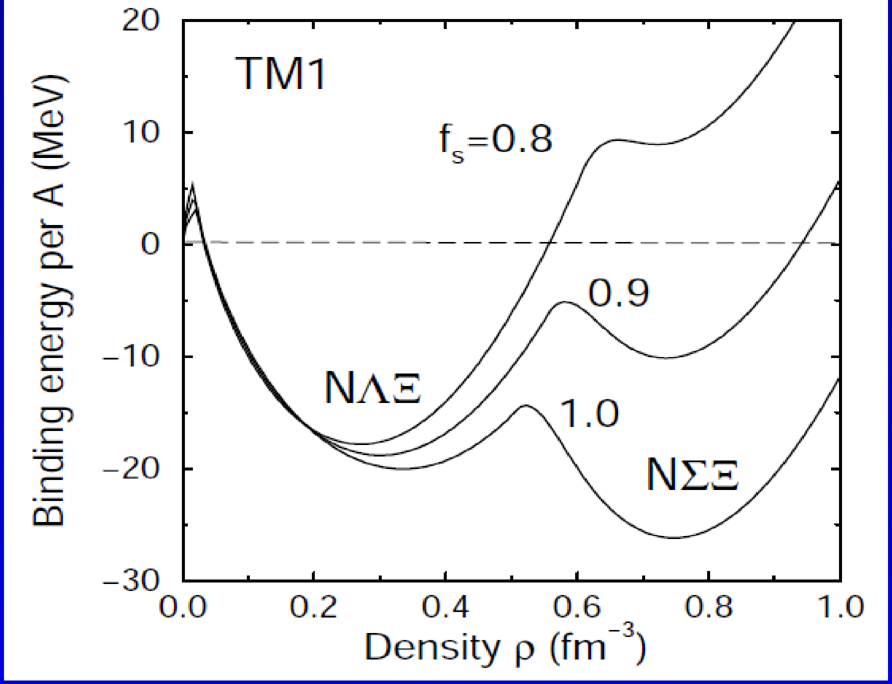
Two families of compact stars:

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.))

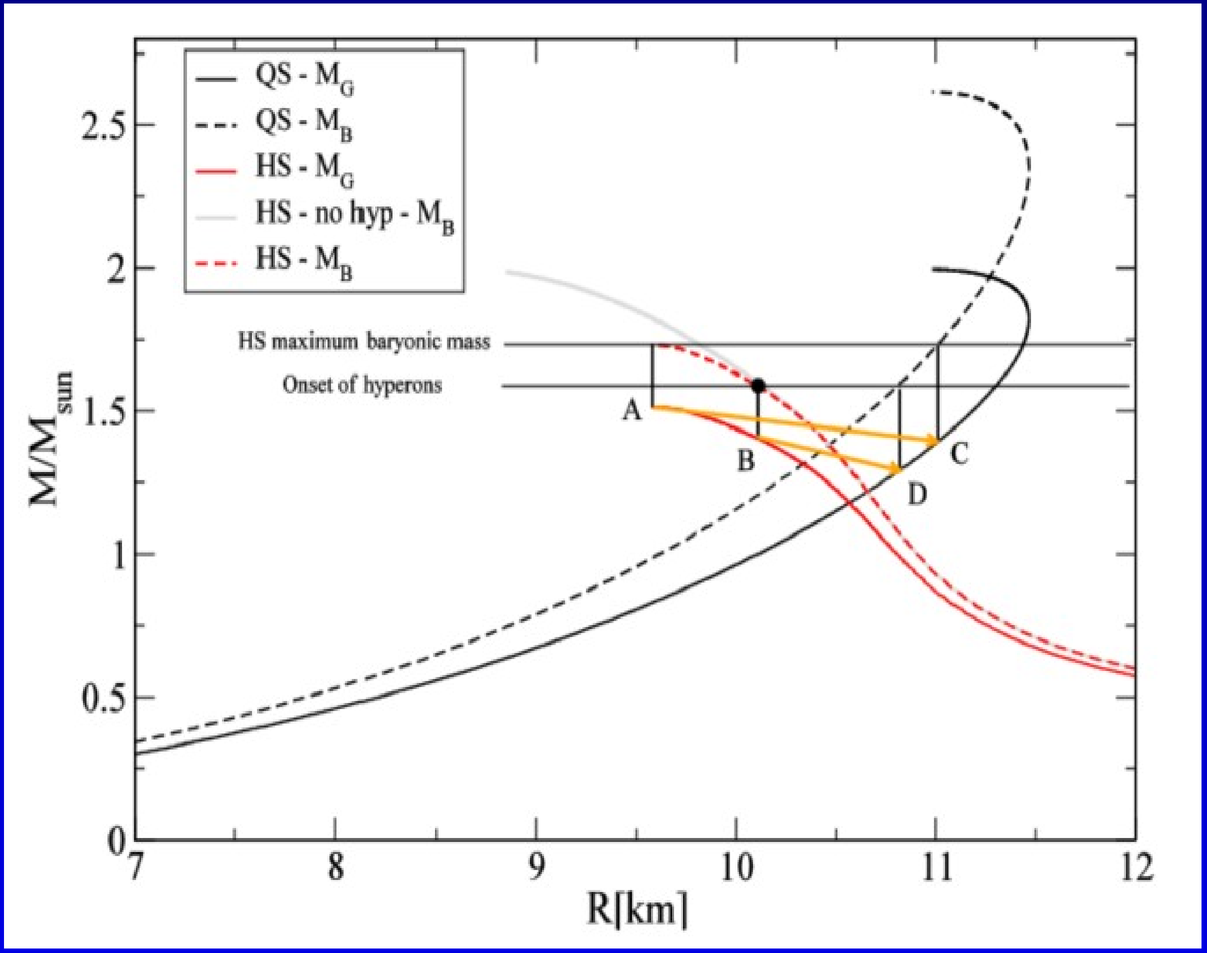
What prevents the conversion of a metastable hadronic star?

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: 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.

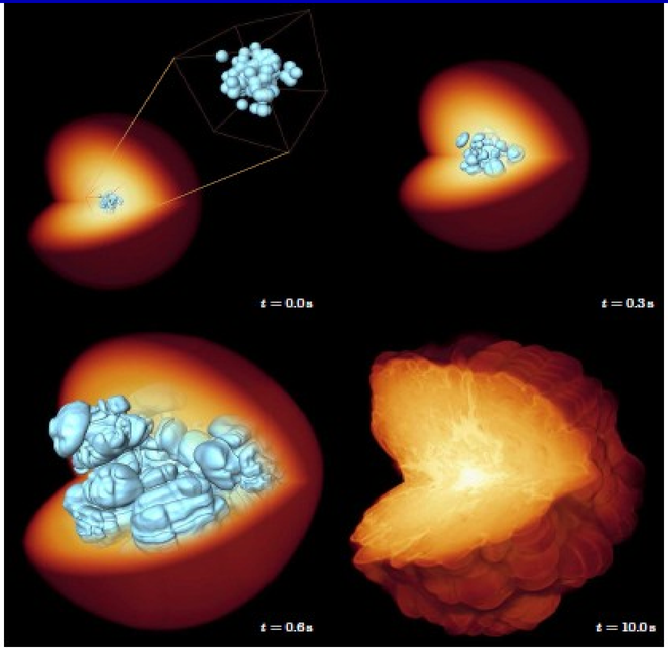


FIGURE 1. Snapshots from a full-star SN Ia simulation starting from a multi-spot ignition scenario. The logarithm of the density is volume rendered indicating the extend of the WD star and the isosurface corresponds to the thermonuclear flame. The last snapshot marks the end of the simulation and is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

Condition for exothermic combustion

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

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

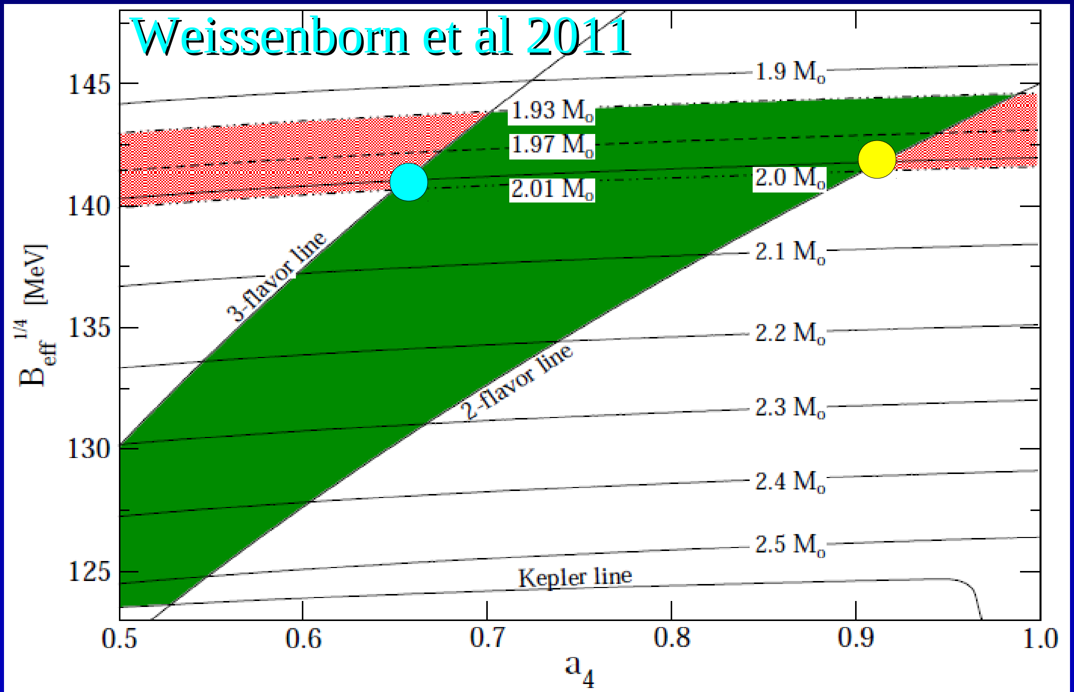
Within a simple parametrization:

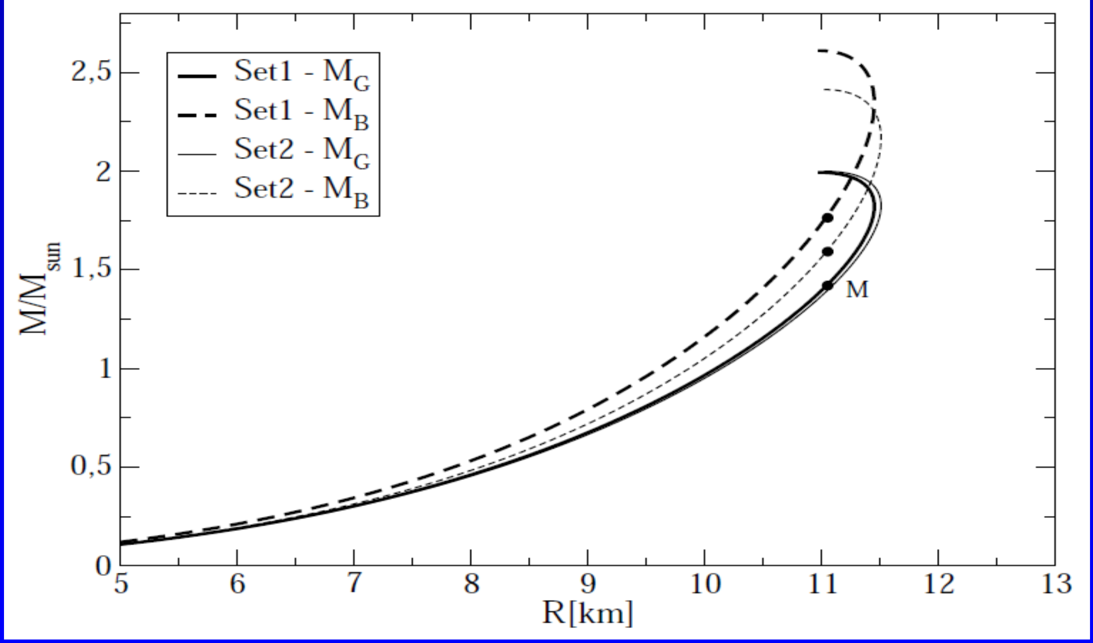
$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1 - a_4) + B_{eff}$$

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

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

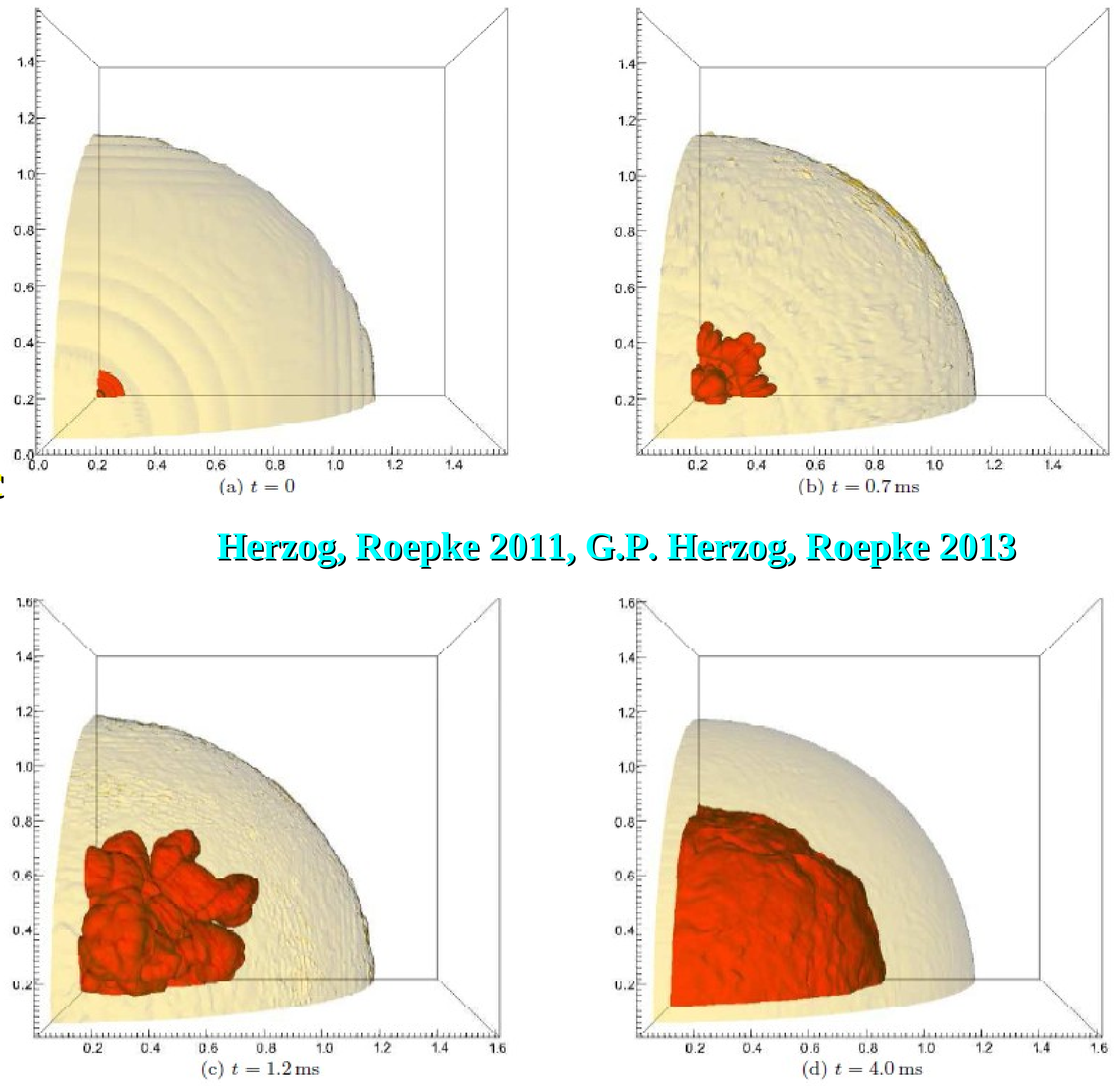
Different QSs binding energy M_B-M_G





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)

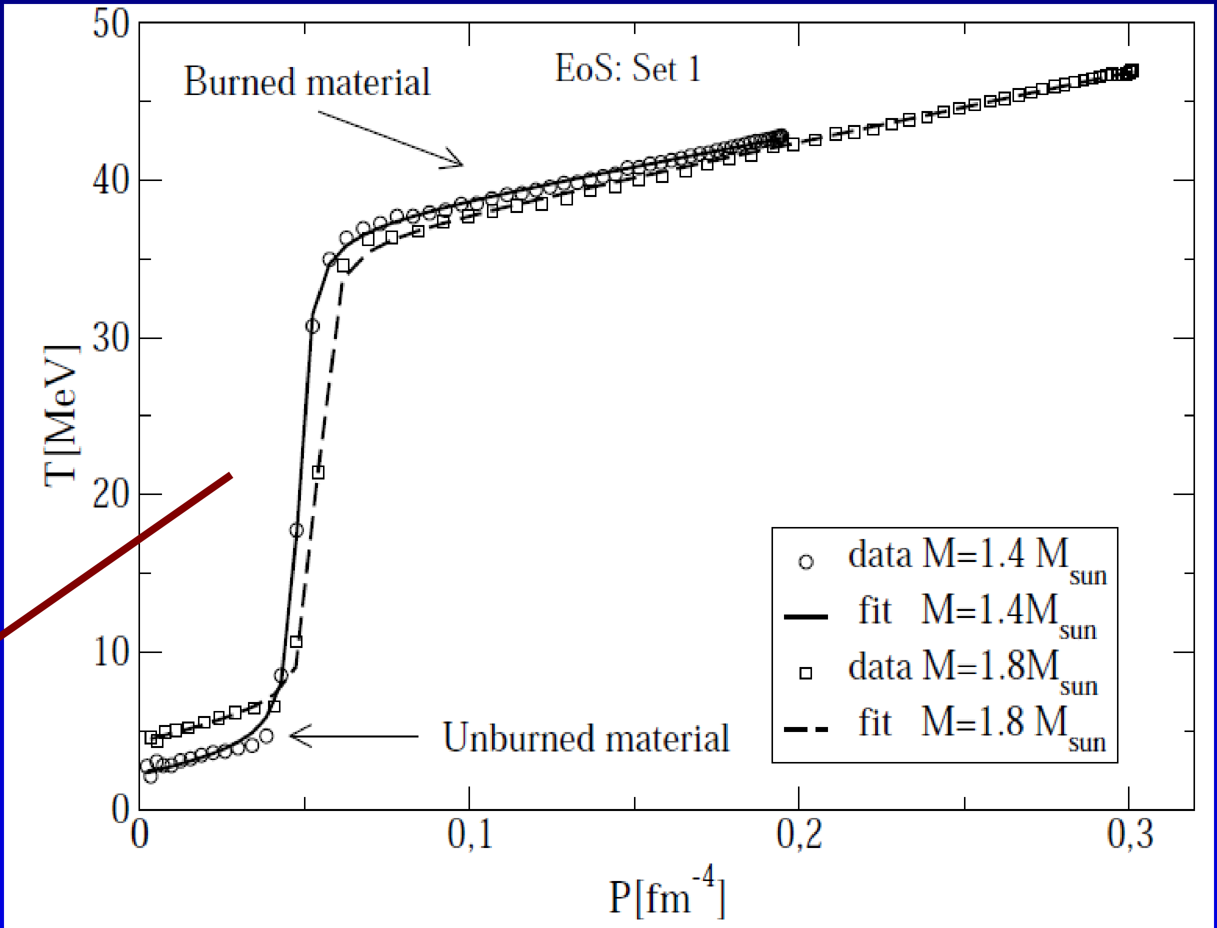


Herzog, Roepke 2011, G.P. Herzog, Roepke 2013

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)

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

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

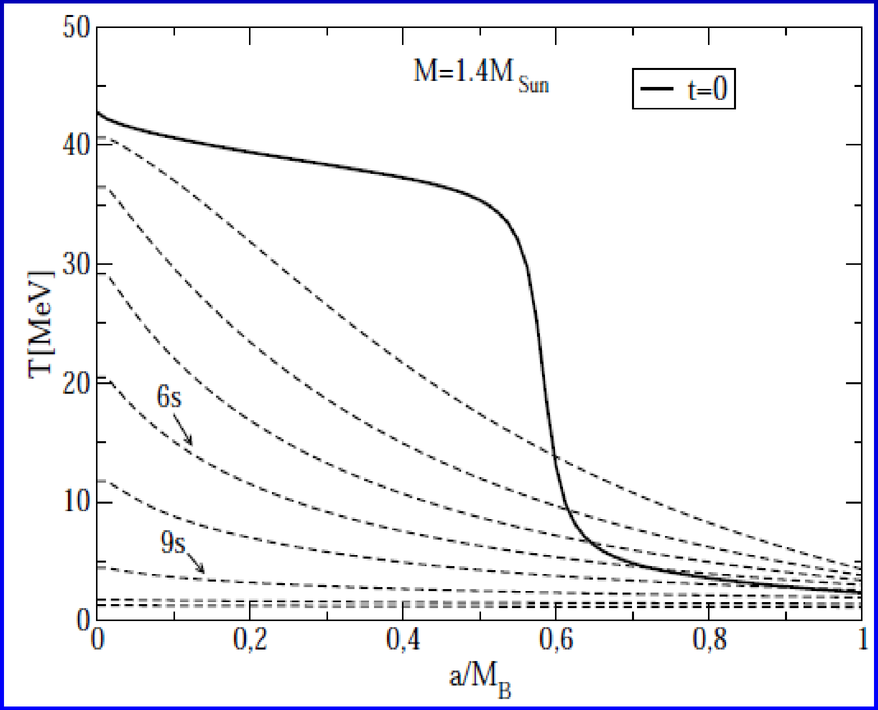
$$\frac{\sigma_S}{V} = \frac{G_F^2 E_\nu^3 \mu_i^2}{5\pi^3}$$

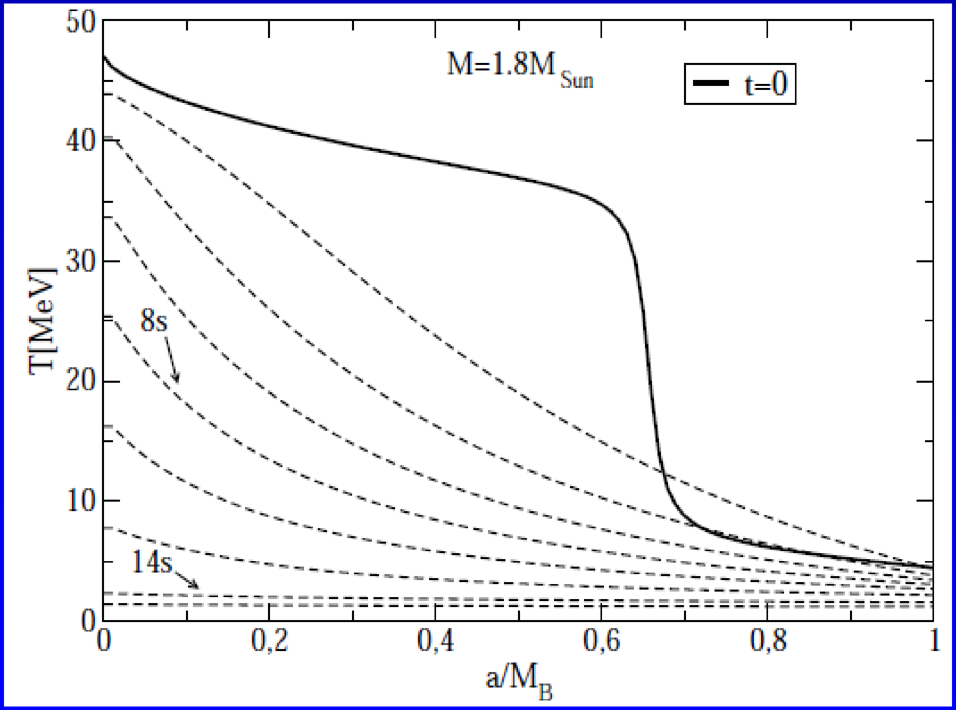
Steiner et al 2001

Expected smaller cooling times with respect to hot neutron stars

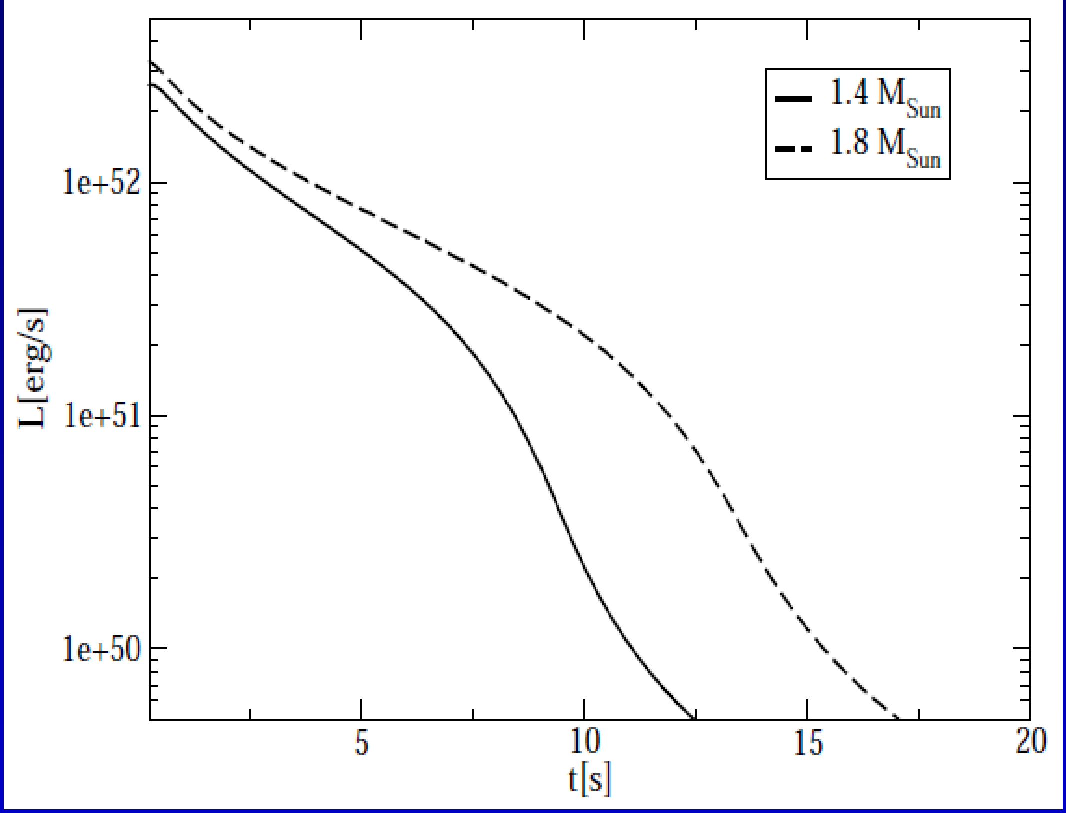
phase	process	λ(T=5 MeV)	λ(T=30 MeV)
Nuclear	$\nu n \to \nu n$	200 m	1 cm
Matter	$\nu_e n \to e^- p$	2 m	4 cm
Unpaired	$\nu q \to \nu q$	350 m	1.6 m
Quarks	$\nu d \to e^- u$	120 m	4 m
CFL	λ_{3B}	100 m	70 cm
	$\nu \phi \to \nu \phi$	>10 km	4 m

Reddy et al 2003





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



Phenomenology II: connection with double GRBs within the protomagnetar model

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)

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

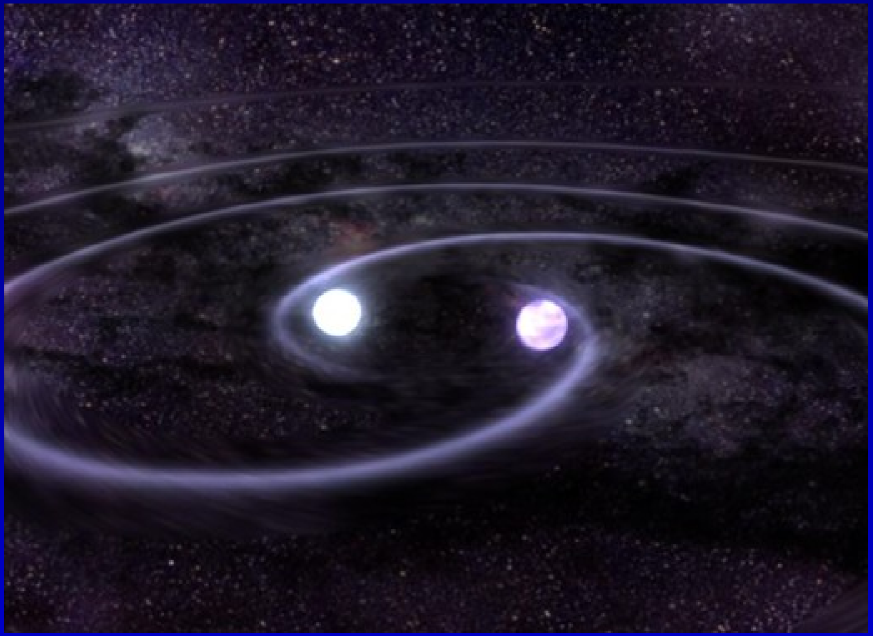
-) New masses and radii measurements challenge nuclear physics: tension between high mass and small radii. A 2.4 Msun candidate already exists. Delta resonances must be taken into account when computing the equation of state: “Delta isobars puzzle”

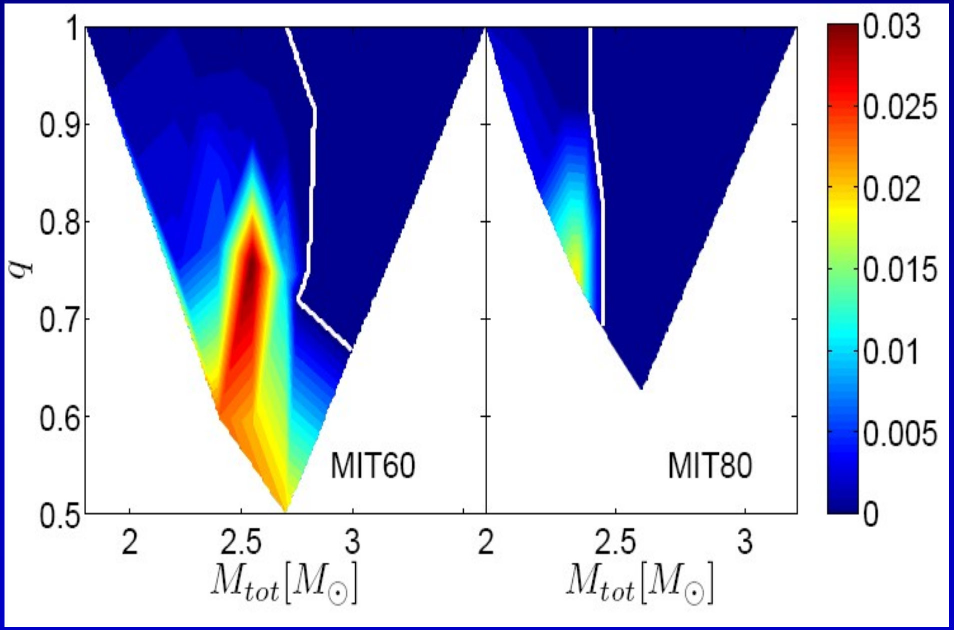
-) LOFT and NICE missions, with a precision of 1km in radii measurements, could hopefully solve the problem

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

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)

Nucleation

(many papers!! done by many people of this workshop!!)

Hot stars: thermal nucleation

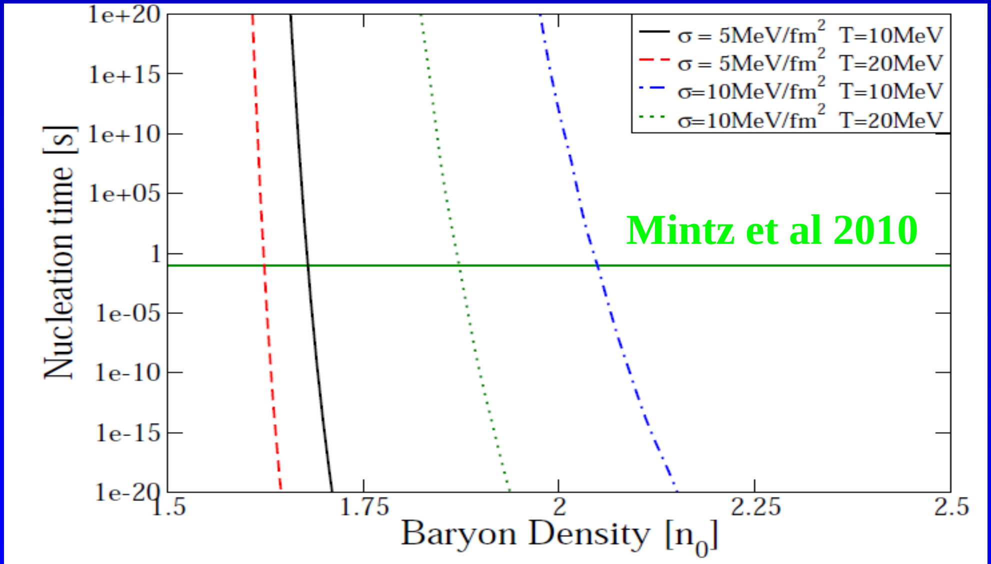
$$\Gamma = T^4 \exp\left[-\frac{16\pi}{3} \frac{\sigma^3}{(\Delta p)^2 T} \right]$$

Cold stars: quantum nucleation, WKB appr.

$$U(R) = \frac{4}{3}\pi R^3 n_q(\mu_q - \mu_h) + 4\pi\sigma R^2$$

$$A(E) = 2\int_{R_-}^{R_+} dR \sqrt{[2M(R) + E - U(R)][U(R) - E]}$$

As expected: strong dependence on surface tension and overpressure



Appendix2

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

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

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

Drago et al 2007