Strangeness in compact stars

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Outline

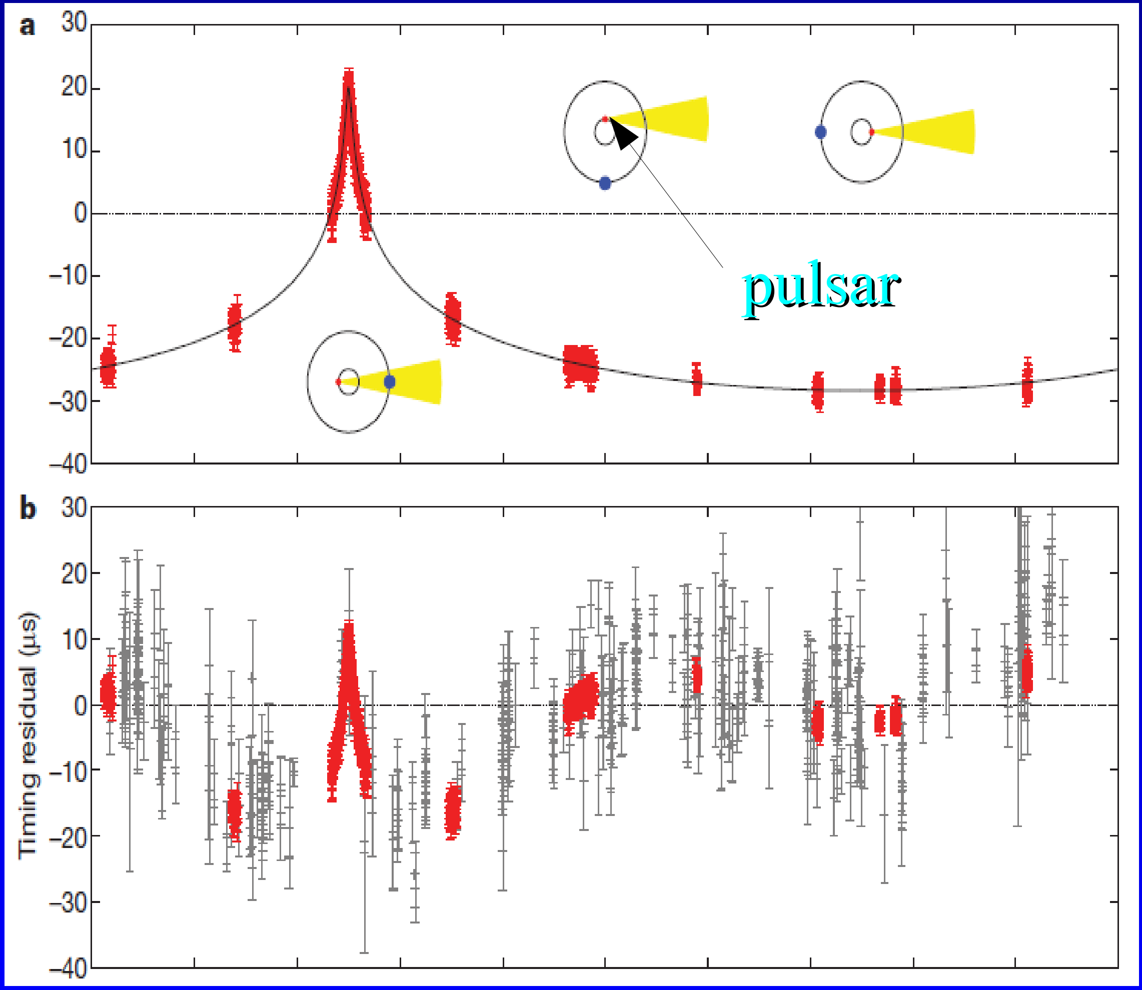
- -) Precise mass measurements: existence of $2M_{sun}$ stars
- -) Implication for the equation of state: nucleons, Δ, hyperons, "deconfined" quarks ?
- -) radii measurements: existence of stars with R <10km (large uncertainties!!)
- -) Two families of compact stars ? Birth of quark stars and connection with explosive events

A milestone for neutron stars Physics: 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.

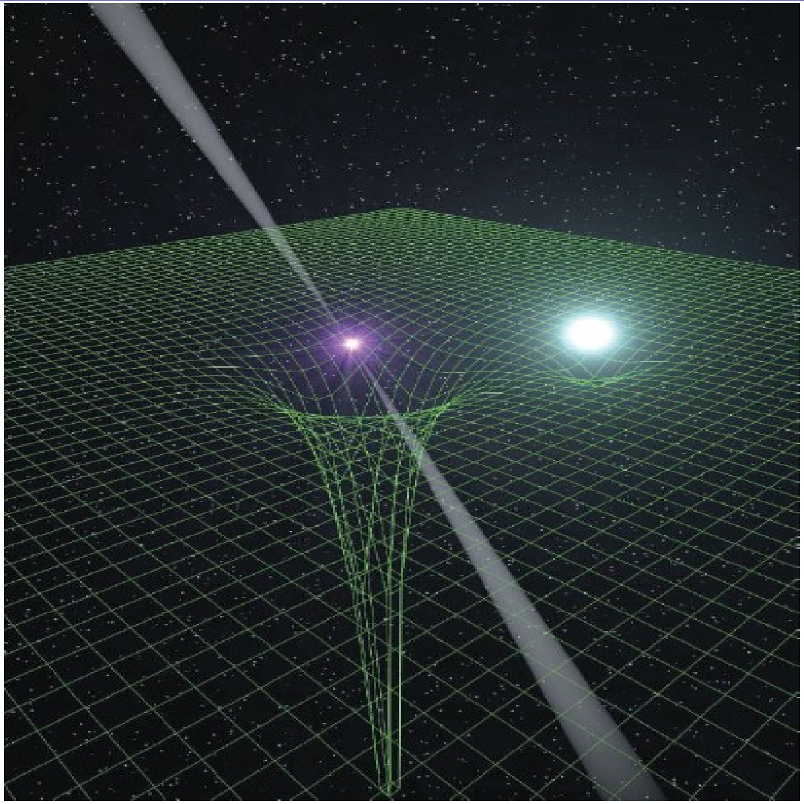
How was it possible?
Great observational and data-analysis set-up...
Luck: massive white dwarf companion 0.5 M_{sun} and the orbital plane almost edge-on.



… recently an 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.

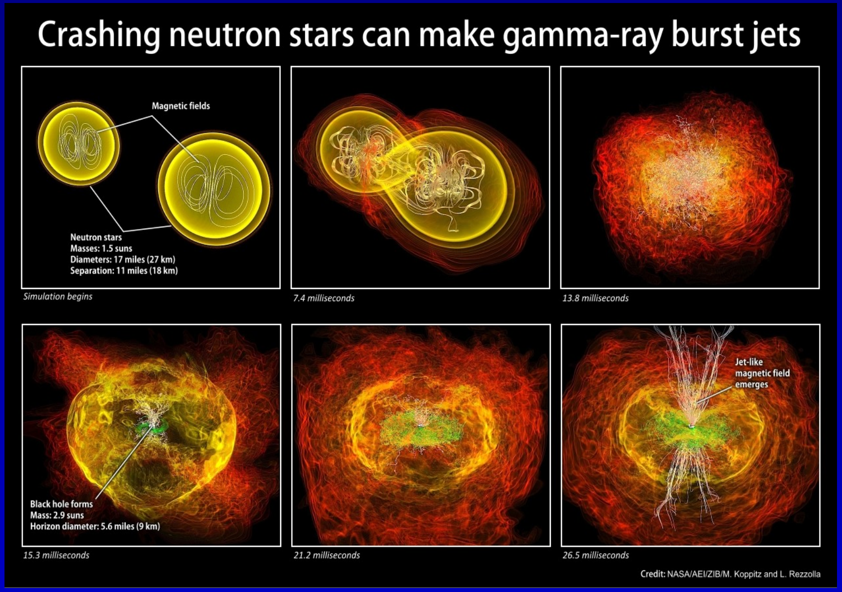
Moreover, the decrease in the orbital period is perfectly in agreement with gravitational waves emission.



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.

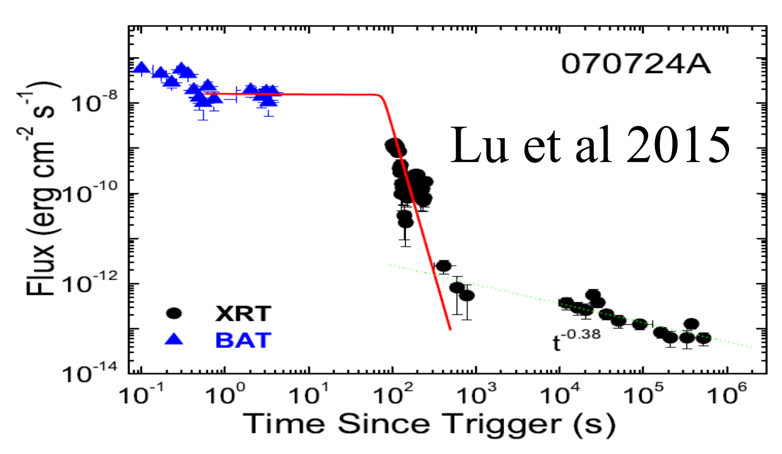
… heavier stars from shortGRB observations

Before SWIFT: energy released 10^{51} ergs, duration few tens of ms.
Inner engine: merger of two neutron stars with masses of about 1.3-1.5 Msun.



NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

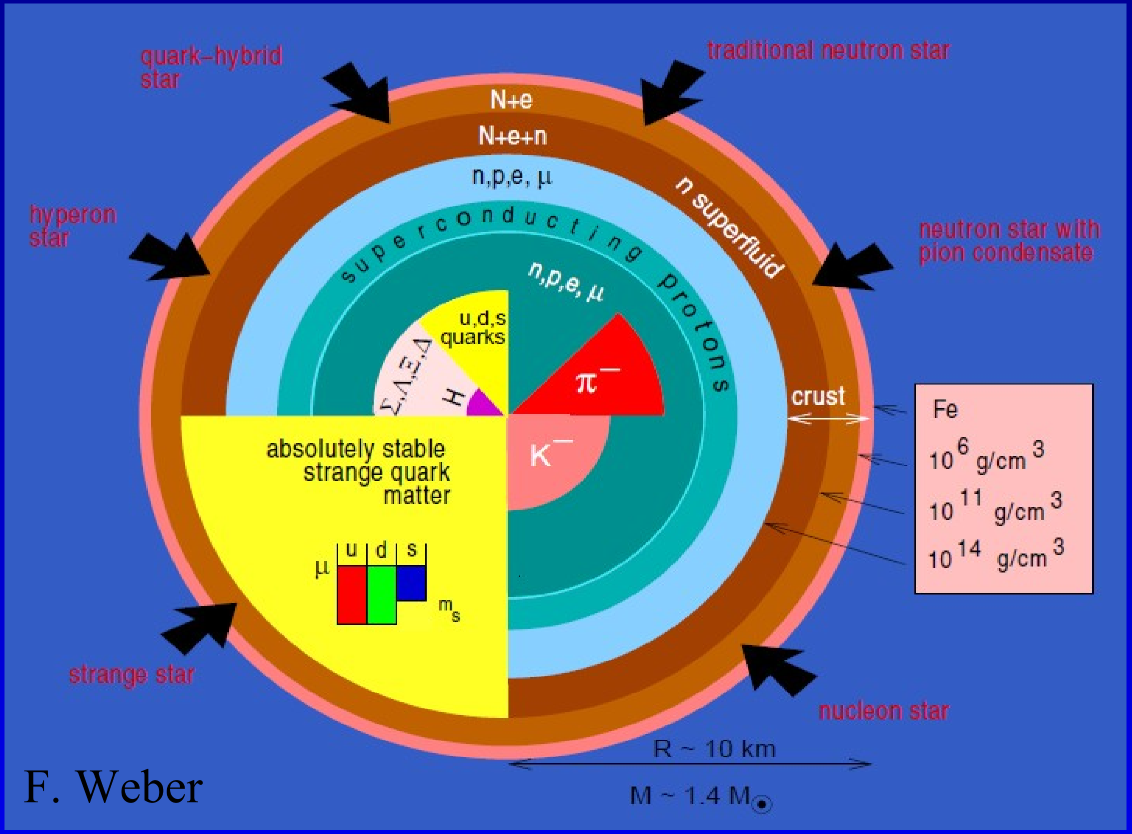
SWIFT has detected many shortGRB with late time activity (10^5sec). This implies that the remnant of the merger is a compact star and not a black hole!!
Maximum mass 2.45 Msun.



Composition of a compact star

-)The equation of state is "under control" up to saturation density (also for asymmetric matter)

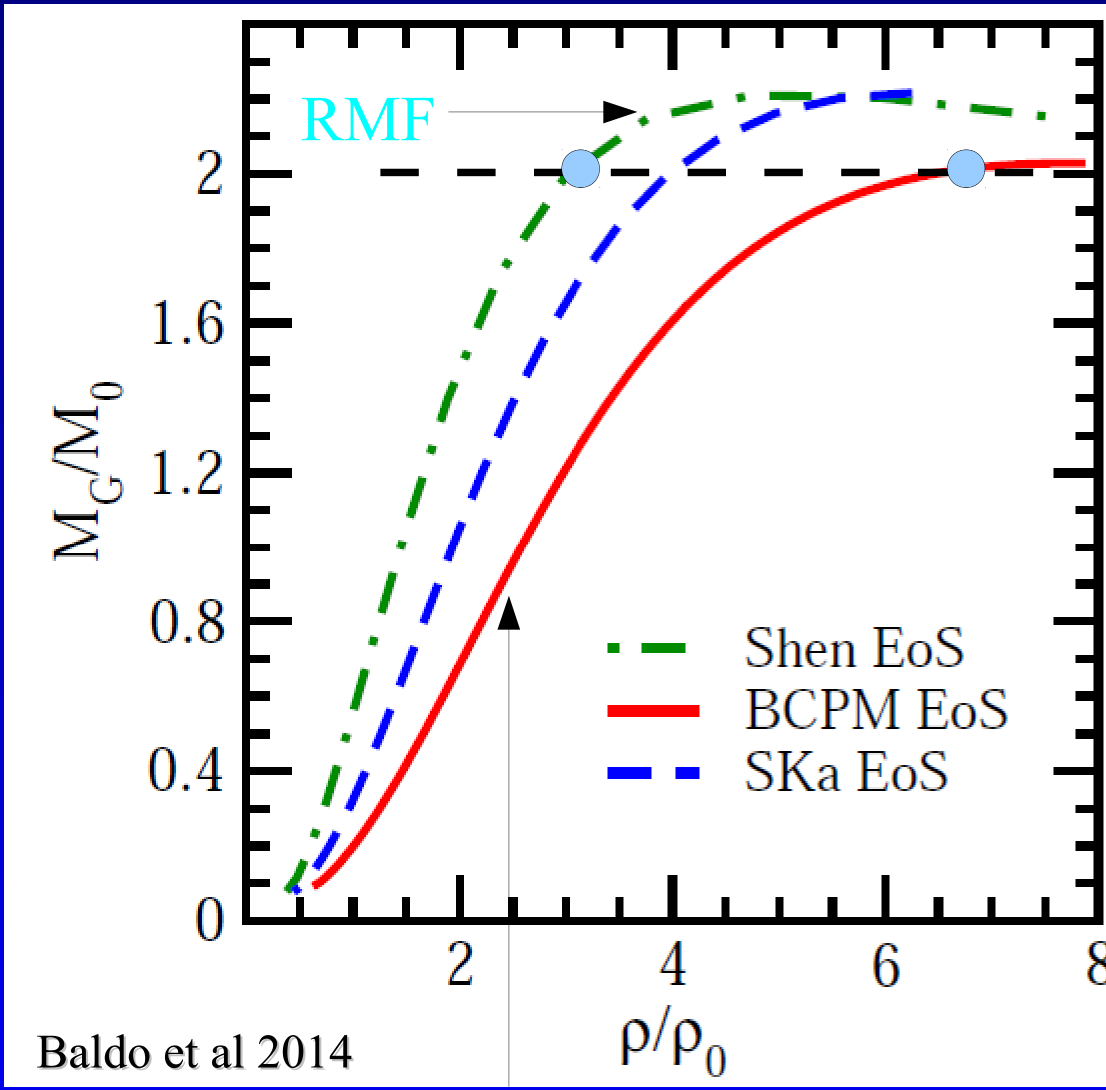
-) Several theoretical possibilites at higher densities (inner core of the star)



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 and scattering data: potential depths of Λ, Σ, Ξ allow to fix three parameters (usually the coupling with a scalar meson, see Schaffner-Bielich & Gal 2000).

Within RMF:

(see Weissenborn, Chatterjee, Schaffner-Bielich 2012)

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

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

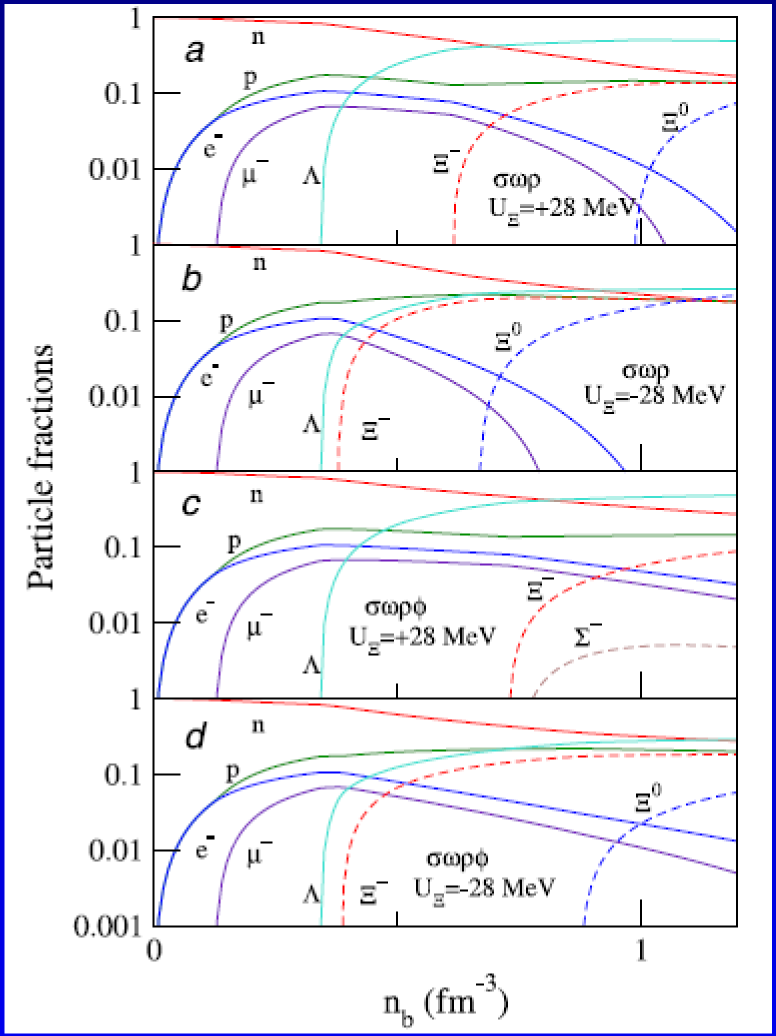
Additional YY interaction

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

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.

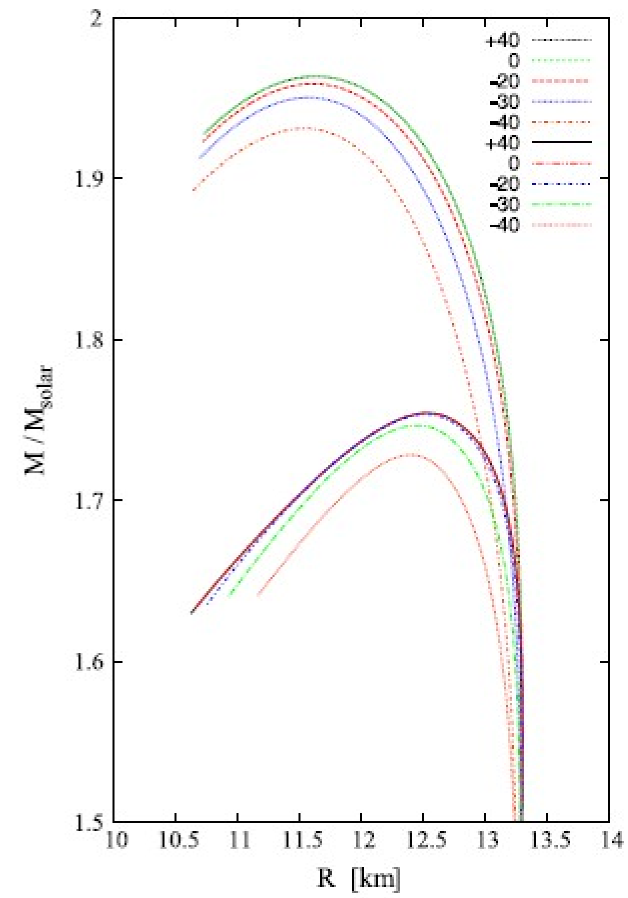
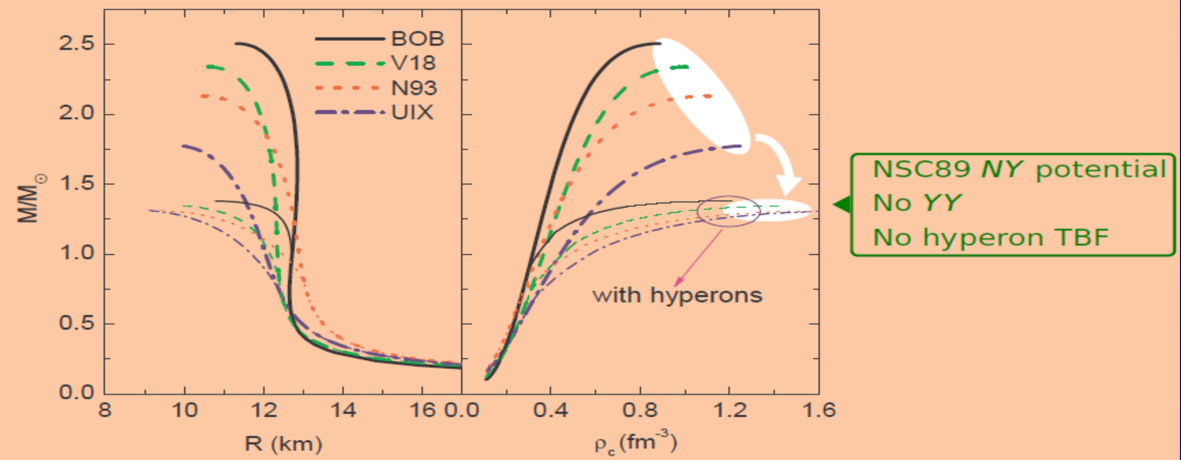


Fig. 2. Mass radius relations for neutron stars obtained with the EoS from Fig. 1. The variation of $U_{\Sigma}^{(N)}$ in “model $\sigma\omega\rho$” cannot account for the observed neutron star mass limit (lower branch), unless the ϕ meson is included in the model (upper branch).

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

Results from microscopic calculations BHF theory:

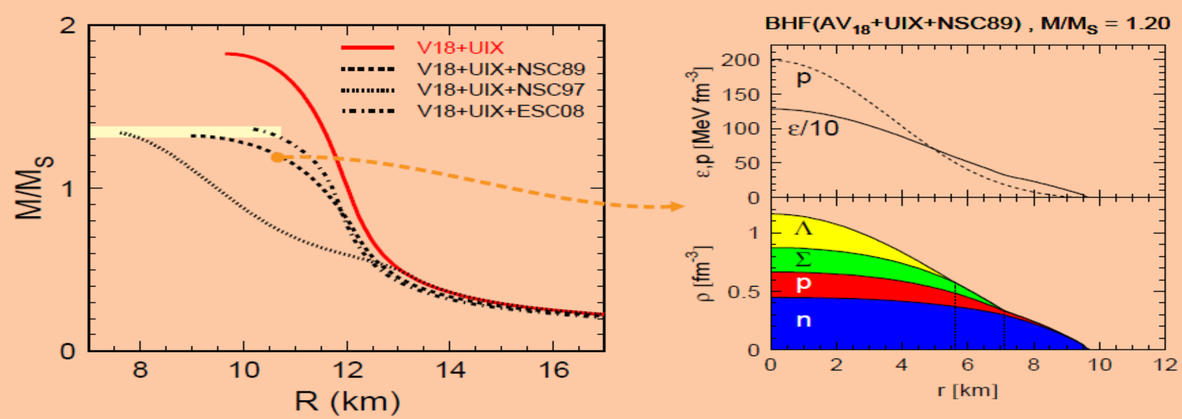
- Mass-radius relations with different nucleonic TBF:



Large variation of M_{max} with nucleonic TBF
Self-regulating softening due to hyperon appearance
(stiffer nucleonic EOS → earlier hyperon onset)

Courtesy of H.F. Schulze

- Using different *NY*,*YY* potentials:

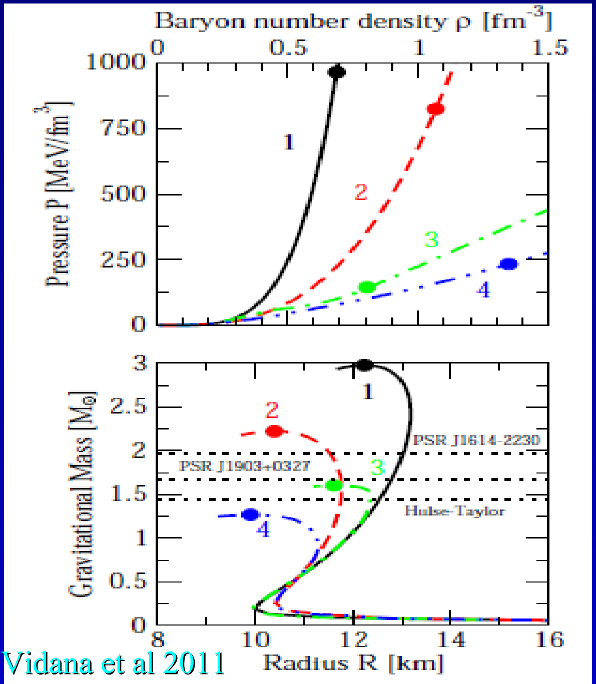


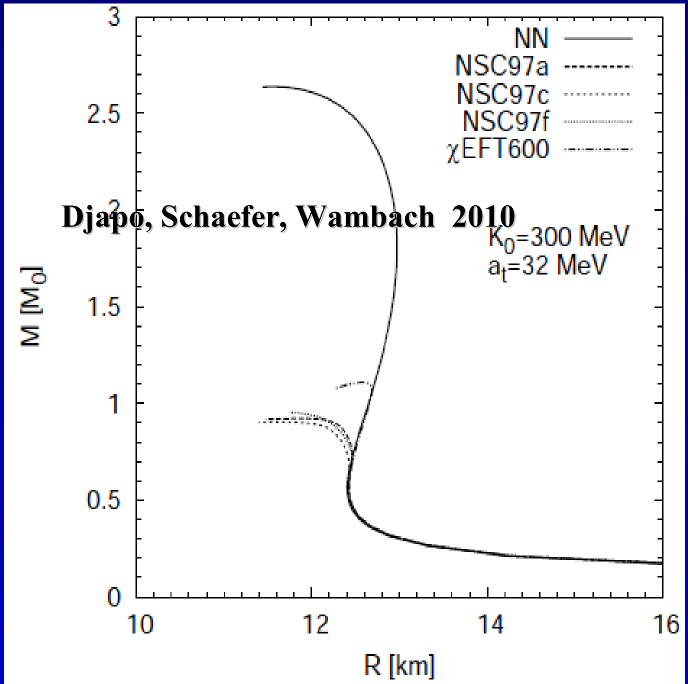
Maximum mass independent of potentials !
Maximum mass too low ($< 1.4\,M_\odot$) !
Proof for "quark" matter inside neutron stars ?

… other dramatic results from microscopic calculations

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

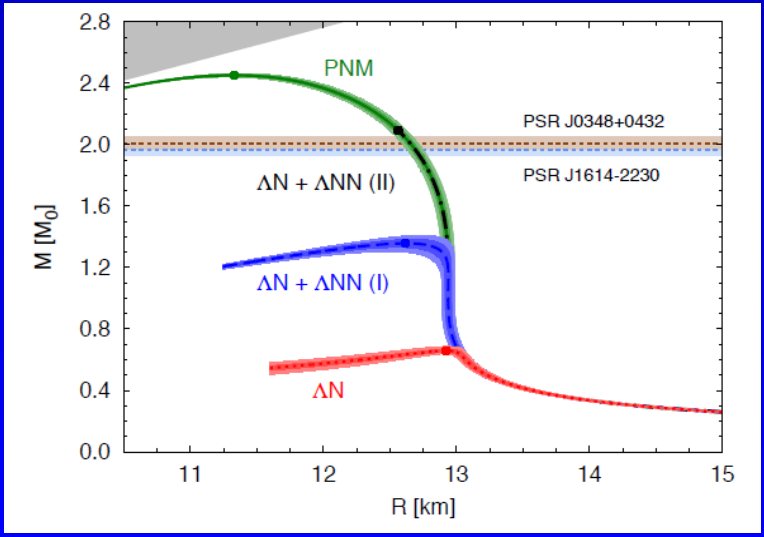
The solution is not just the "let's use only nucleons"





Quantum MonteCarlo simulations
(Lonardoni PRL 2015)

A strong NNΛ repulsion prevents the appearance of Λ for densities up to ~0.6fm^-3



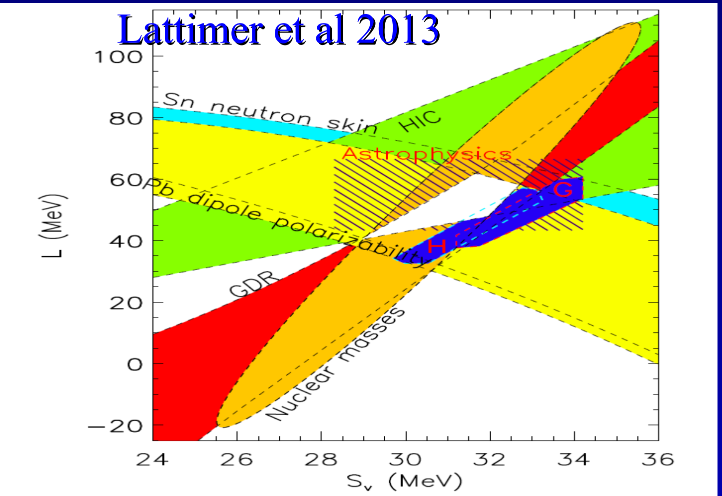
What about Δ?

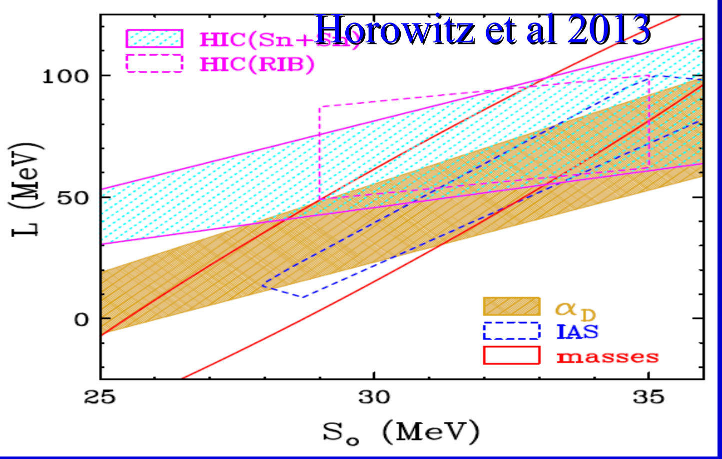
Symmetry energy: the L parameter

Symmetry energy and its density derivative

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

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





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

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

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

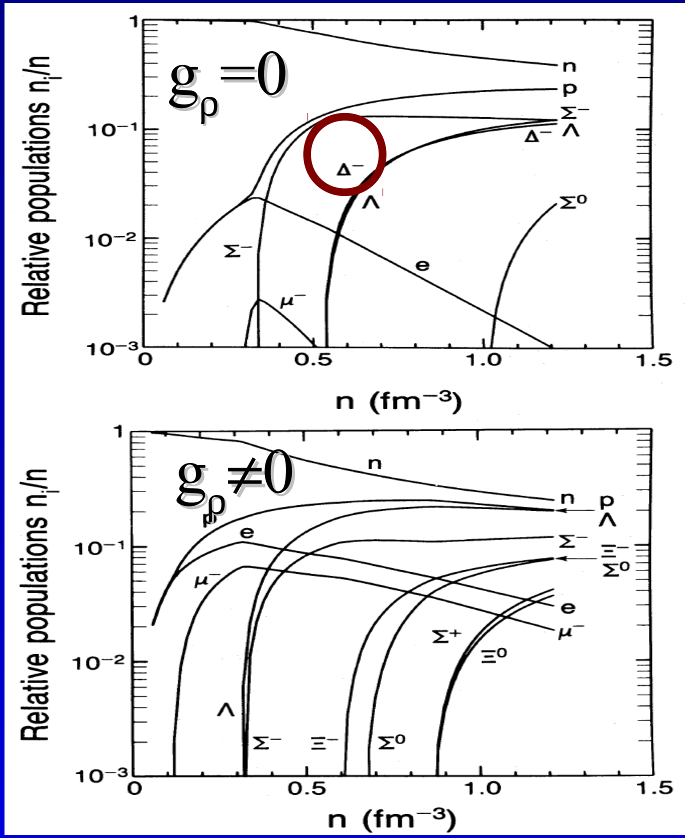
Only S_v could be fixed through g_ρ

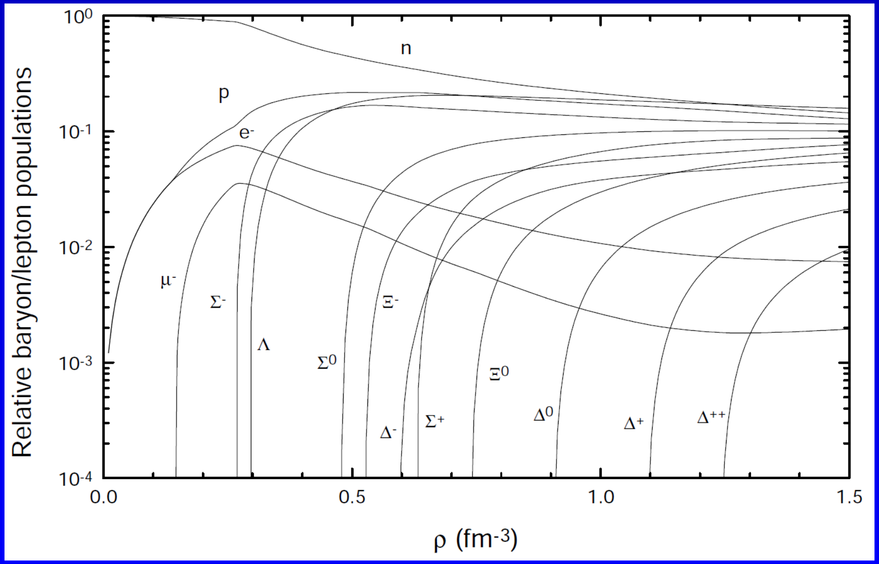
… it turns out that in the GM1-2-3 parametrizations L ~ 80 MeV thus higher than the values indicated by the recent analysis of Lattimer & Lim.

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).



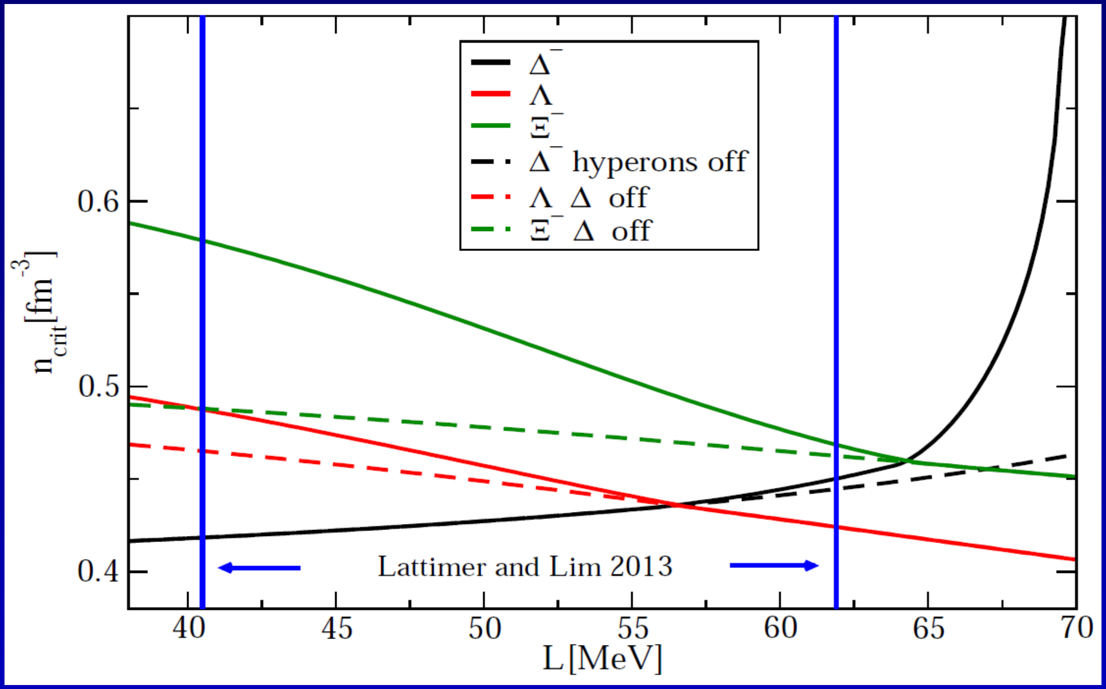


Δ^- easier to form in RHF calculations (see Huber et al 1998) due to the smaller value of g_ρ

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-Gal 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

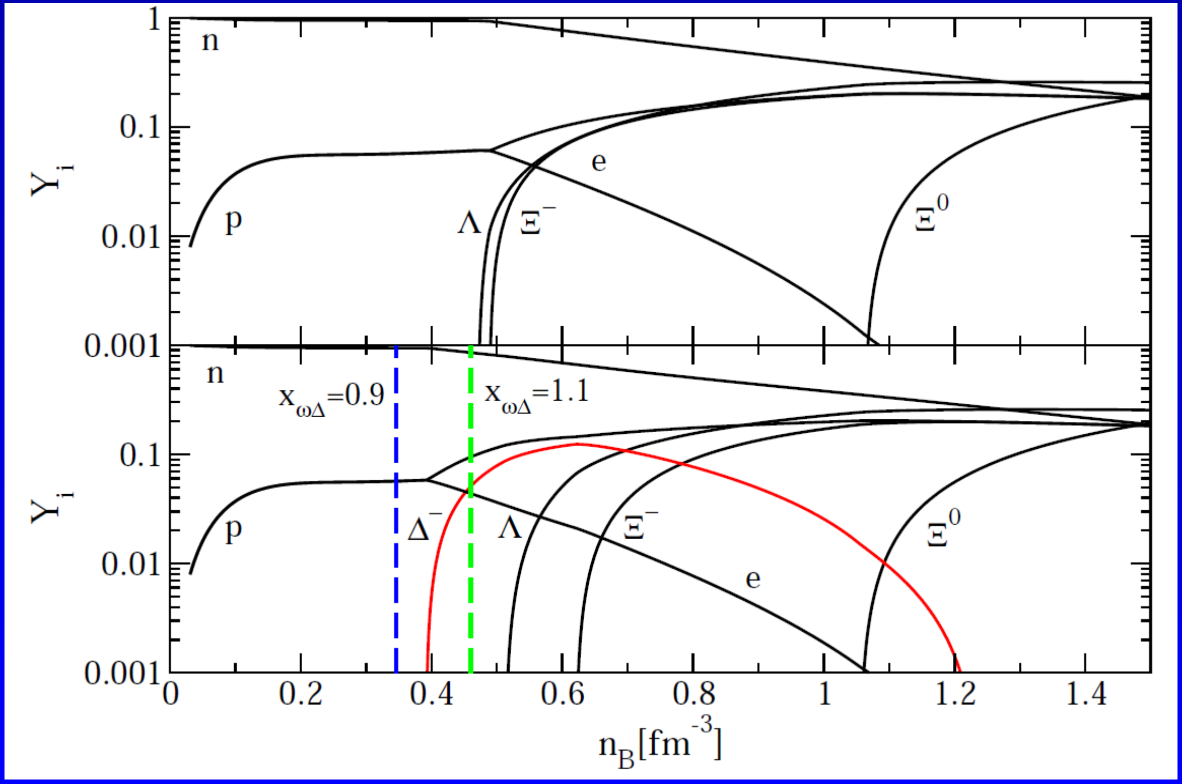
$$
\begin{aligned}
\mathcal{L} \;=\; & \bar{\Psi}\left[i\partial\!\!\!/ - g_\omega \omega\!\!\!/ - \tfrac{1}{2} g_\rho \vec{\rho}\!\!\!/ \cdot \vec{\tau} - M + g_\sigma \sigma - \tfrac{1}{2} e \left(1+\tau_3\right) A\!\!\!/\right] \Psi + \tfrac{1}{2}\left(\partial_\mu \sigma\right)^2 \\
& - V(\sigma)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

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 similar or even deeper than the nucleon potential. Several phenomenological and theoretical analyses lead to similar conclusions.

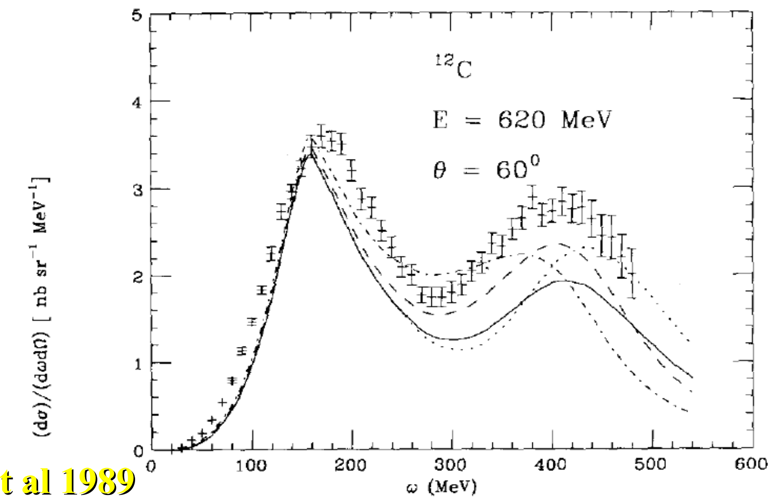


Fig. 13. Cross section for electron scattering on ^{12}C at incident electron energy $E = 620$ MeV and scattering angle $\theta = 60°$ as a function of energy transfer ω for standard nucleon and different Δ-couplings. The lines are the results for the sum of the contribution from nucleon knockout and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

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

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

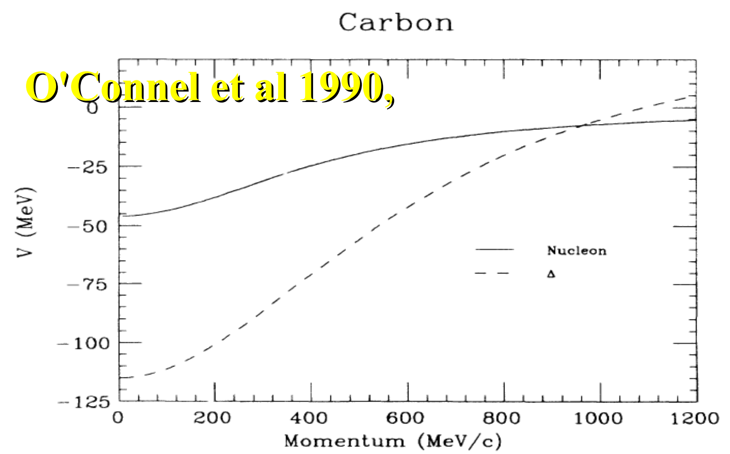
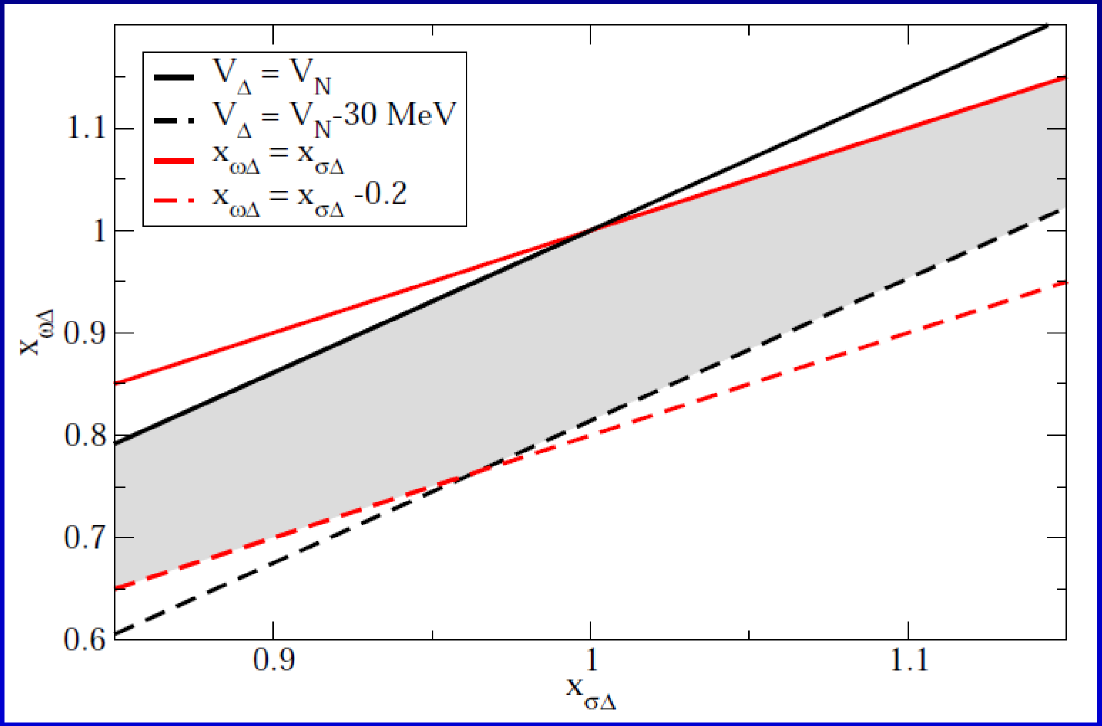


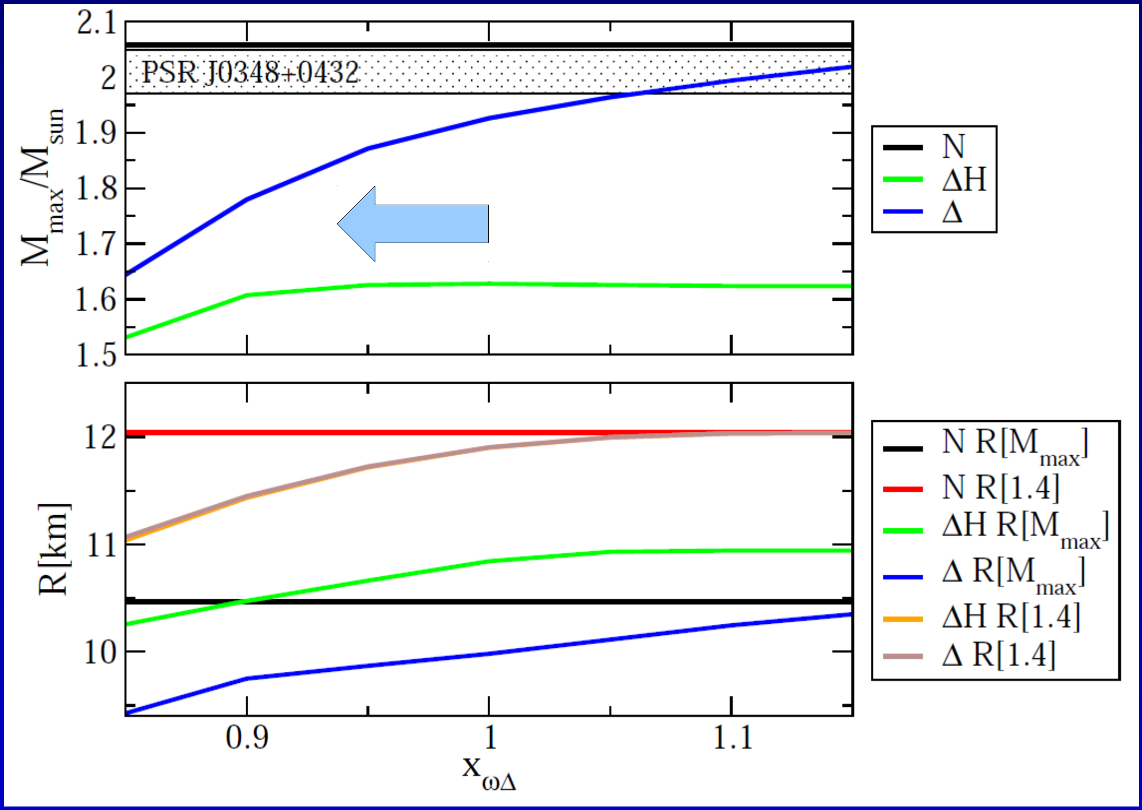
FIG. 4. Phenomenological nucleon-nucleus, solid line, and Δ nucleus, dashed line, momentum-dependent potentials for C.

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.

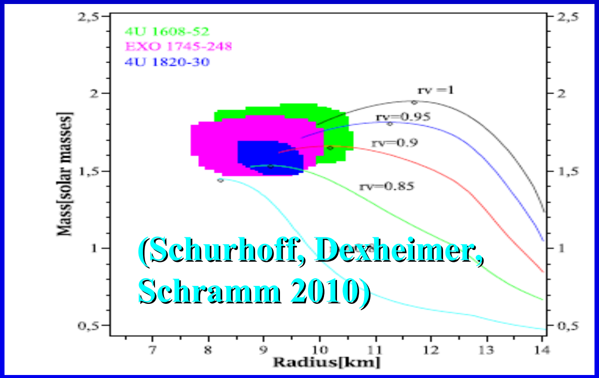


Implications for compact stars ?

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



See also:



Punchline2: beside the "hyperon puzzle" is there also a "delta isobars puzzle"?

To do: include the imaginary part of the delta self-energy in the equation of state calculations.

Simple estimates with a Breit-Wigner-like distribution. Critical density within the range of neutron stars central densities.

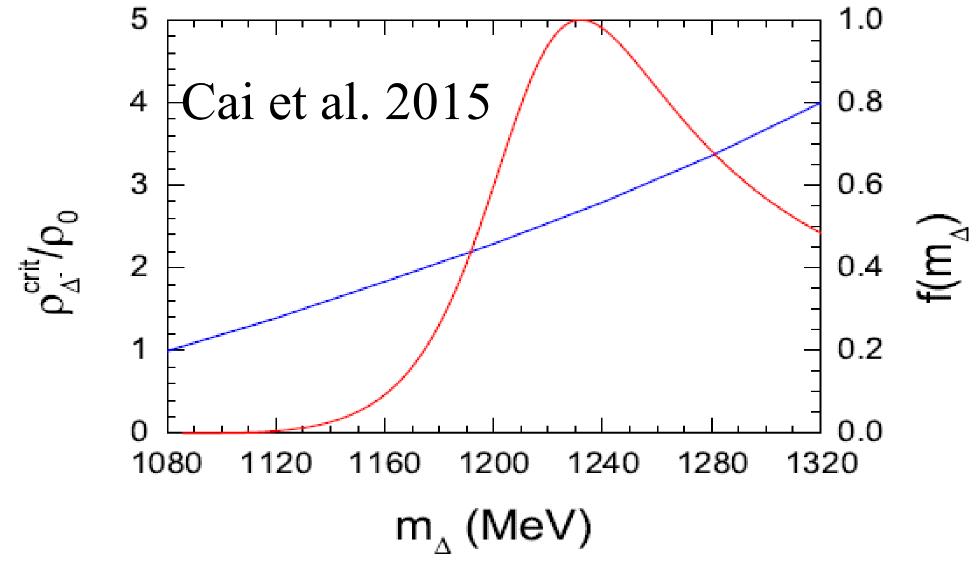
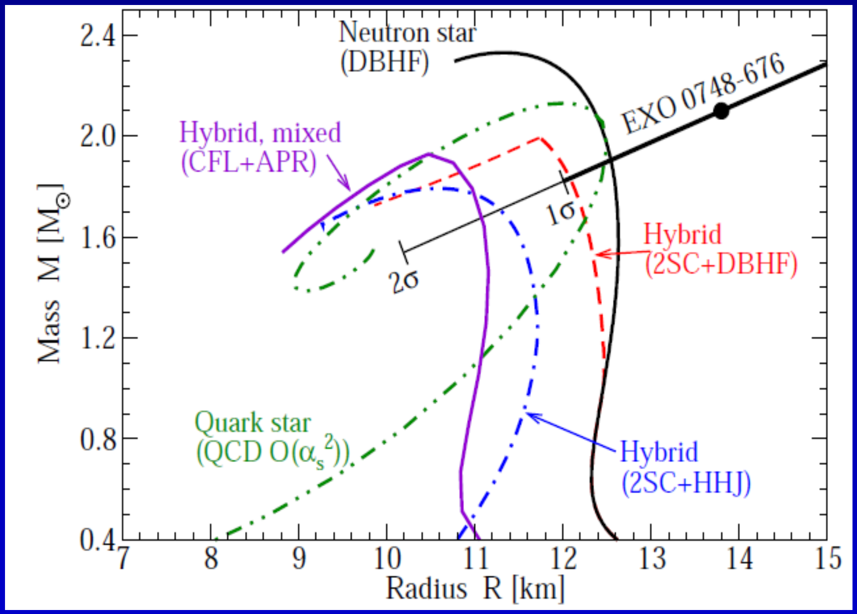


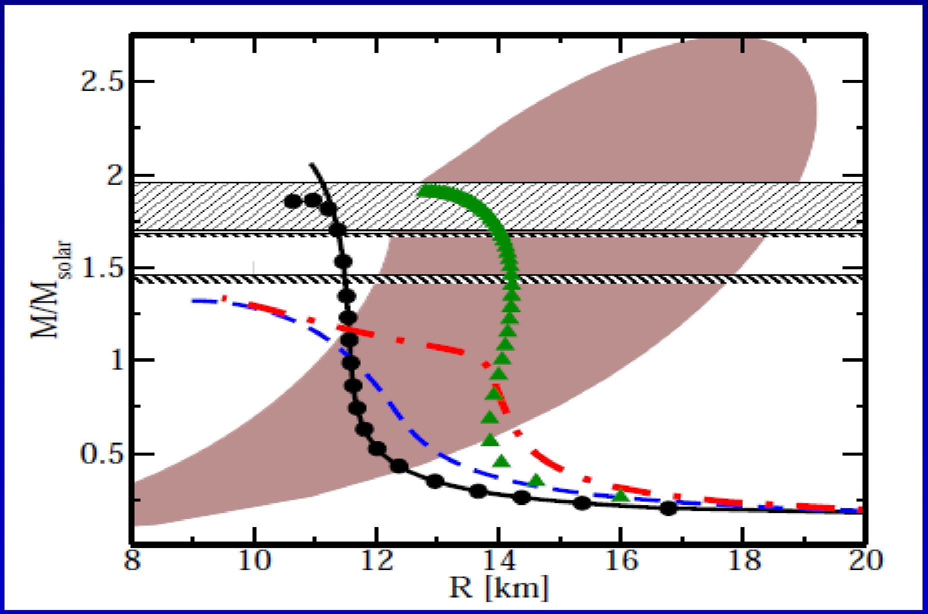
Figure 3: (Color Online) The Delta mass m_Δ dependence of the critical density $\rho^{crit}_{\Delta^-}$ for Δ^- formation in neutron stars (blue) and the Breit-Wigner mass distribution of Delta resonances in free-space (red).

$$f(m_\Delta) = \frac{1}{4}\frac{\Gamma^2(m_\Delta)}{(m_\Delta - m^0_\Delta)^2 + \Gamma^2(m_\Delta)/4}$$

Exotica

Stars containing quark matter?





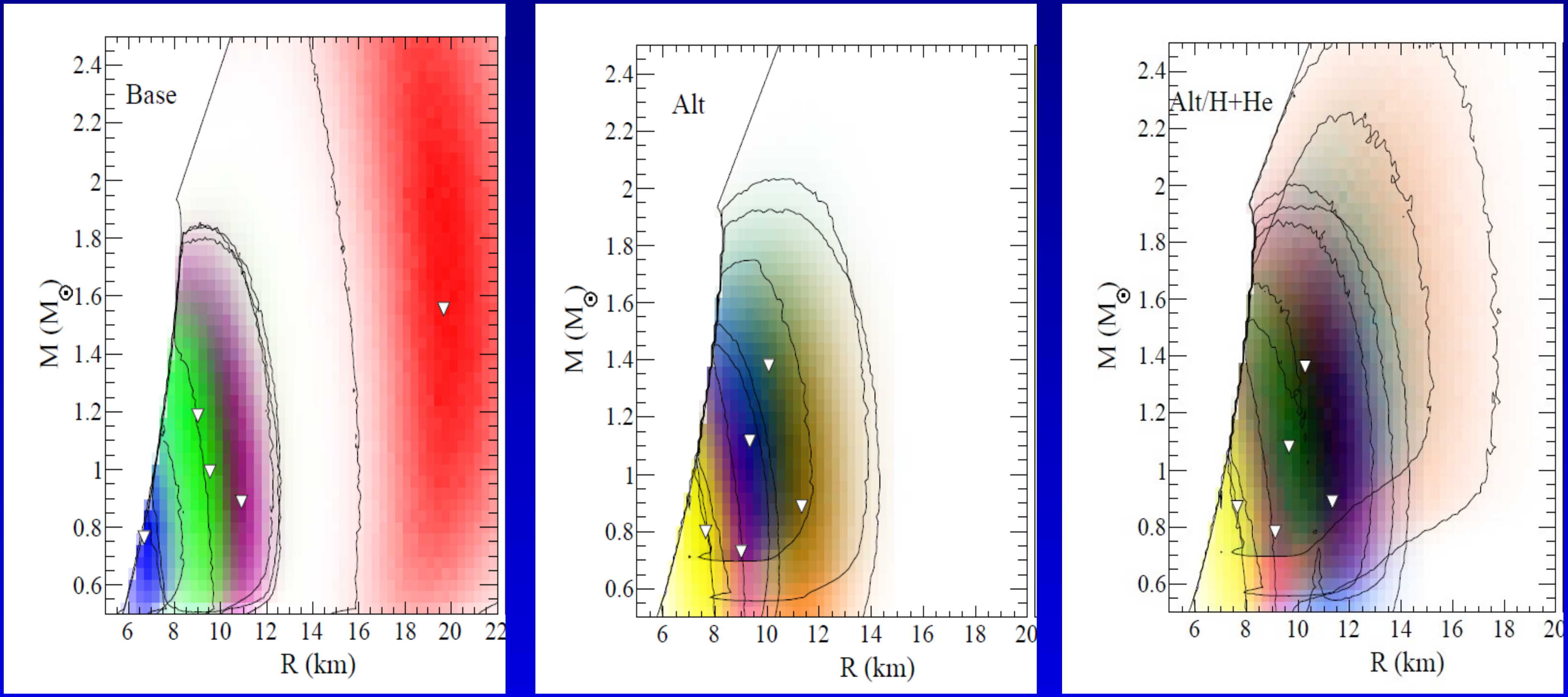
Alford et al Nature 2006

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"

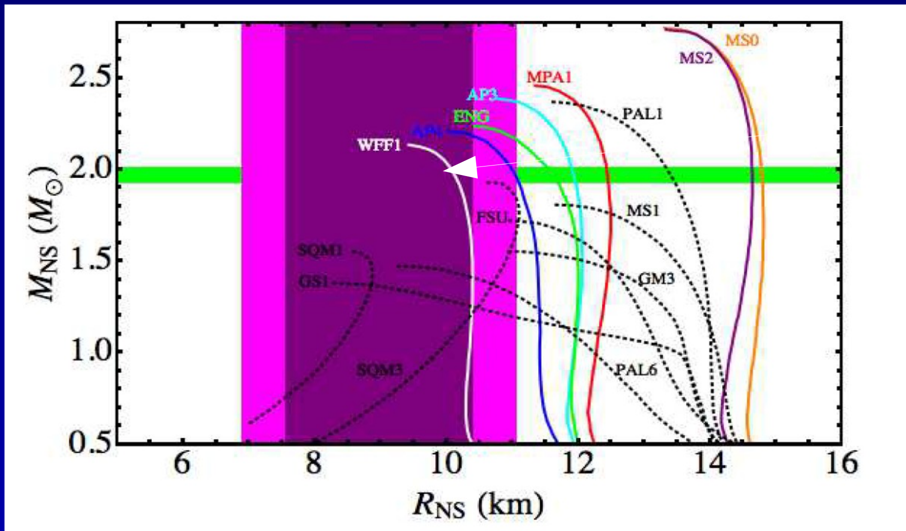
Before the discoveries of the two $2M_{sun}$ stars!!

Recent radii measurements

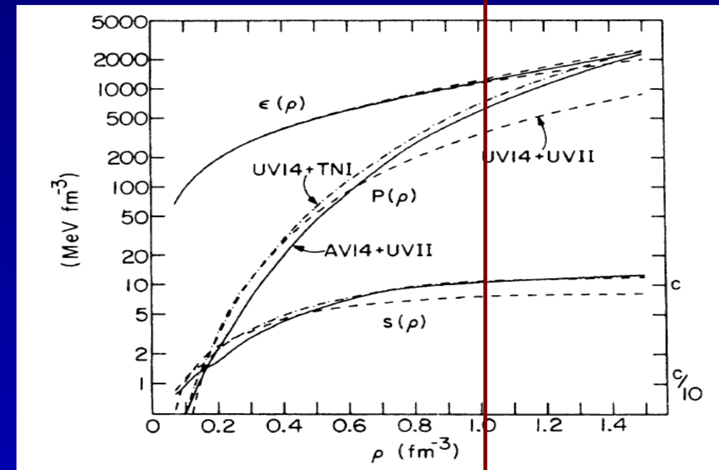


Guillot et al. ApJ772(2013)7

Lattimer and Steiner 1305.3242



Wiringa et al 1988, nice, but:



R=9.1±1.3 km. Updated to 9.4±1.2 (Guillot et al. 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:

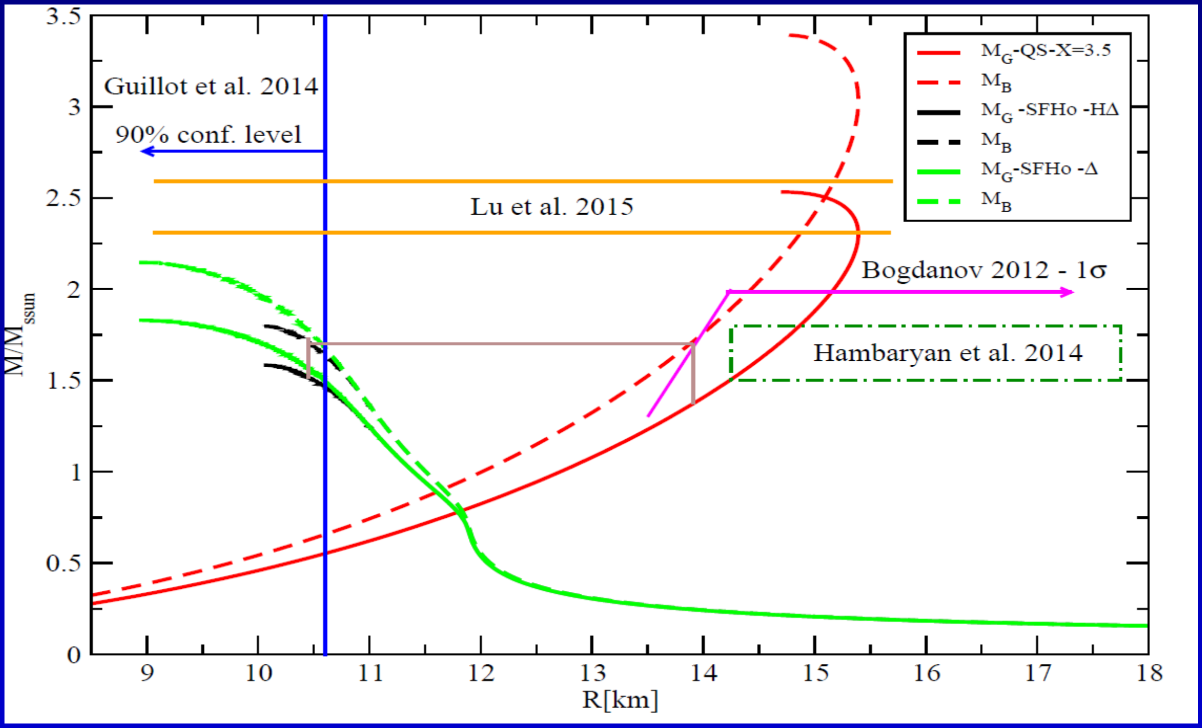
high masses → stiff equation of state

small radii → soft equation of state

→ large central densities

→ formation of new particles

Drago, Lavagno, G.P. 2013 -2014-2015



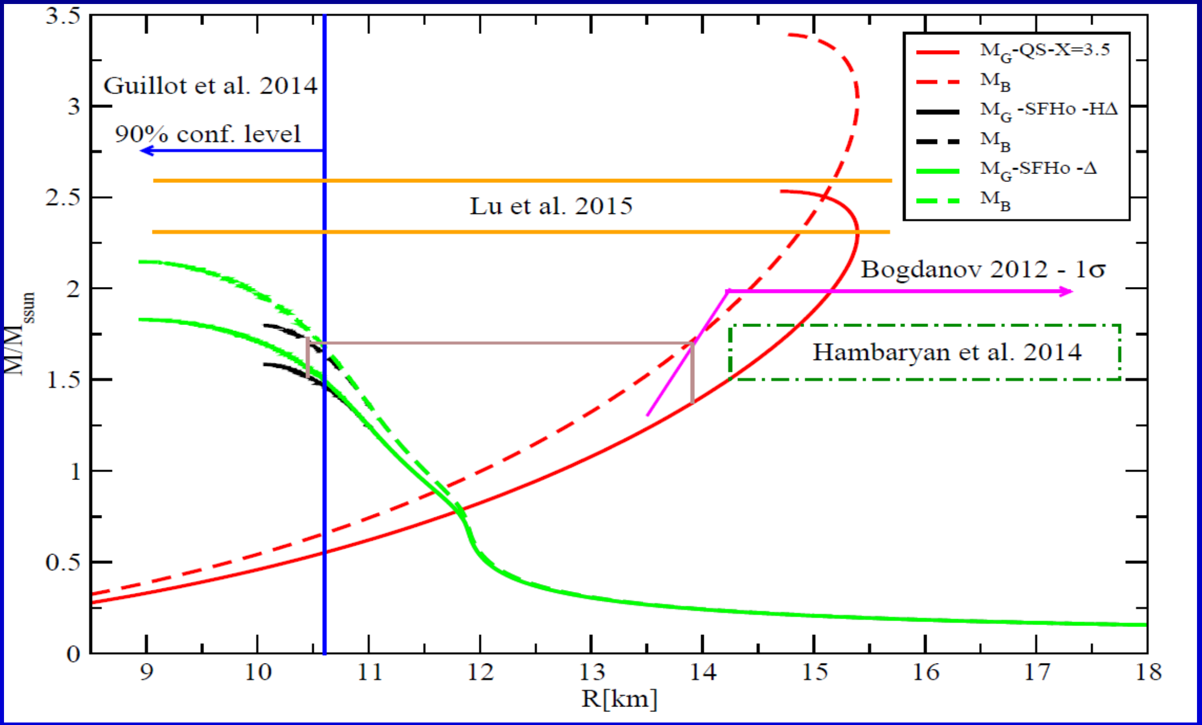
(results from RMF models for hadronic matter and simple parametrizations of the pQCD results for quark mater)

Two families of compact stars:

1) low mass (up to ~1.5 Msun) and small radii (down to 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.))

How to populate the quark star branch? Quark stars are more bound: at a fixed total baryon number they have a smaller gravitational mass wrt hadronic stars



How does this conversion occur? Time scales for the conversion and energy released?

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.

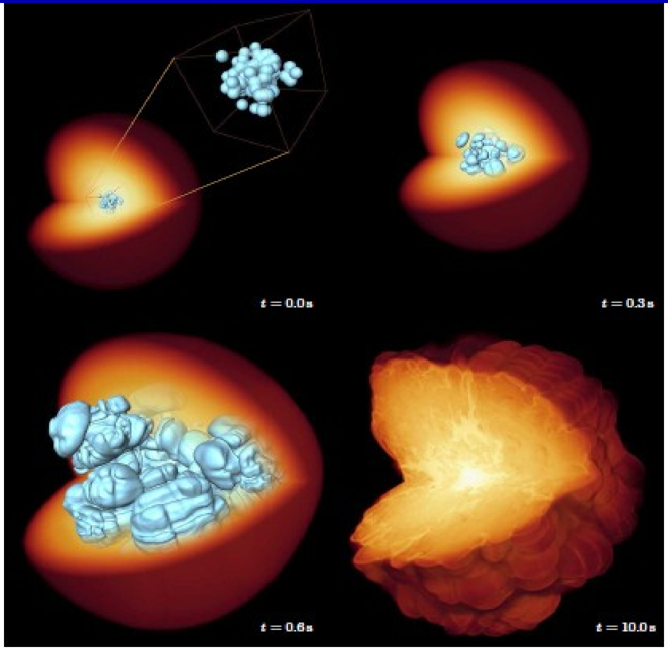


FIGURE 1. Snapshots from a full-star SN Ia simulation starting from a multi-spot ignition scenario. The logarithm of the density is volume rendered indicating the extend of the WD star and the isosurface corresponds to the thermonuclear flame. The last snapshot marks the end of the simulation and is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

Condition for exothermic combustion

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

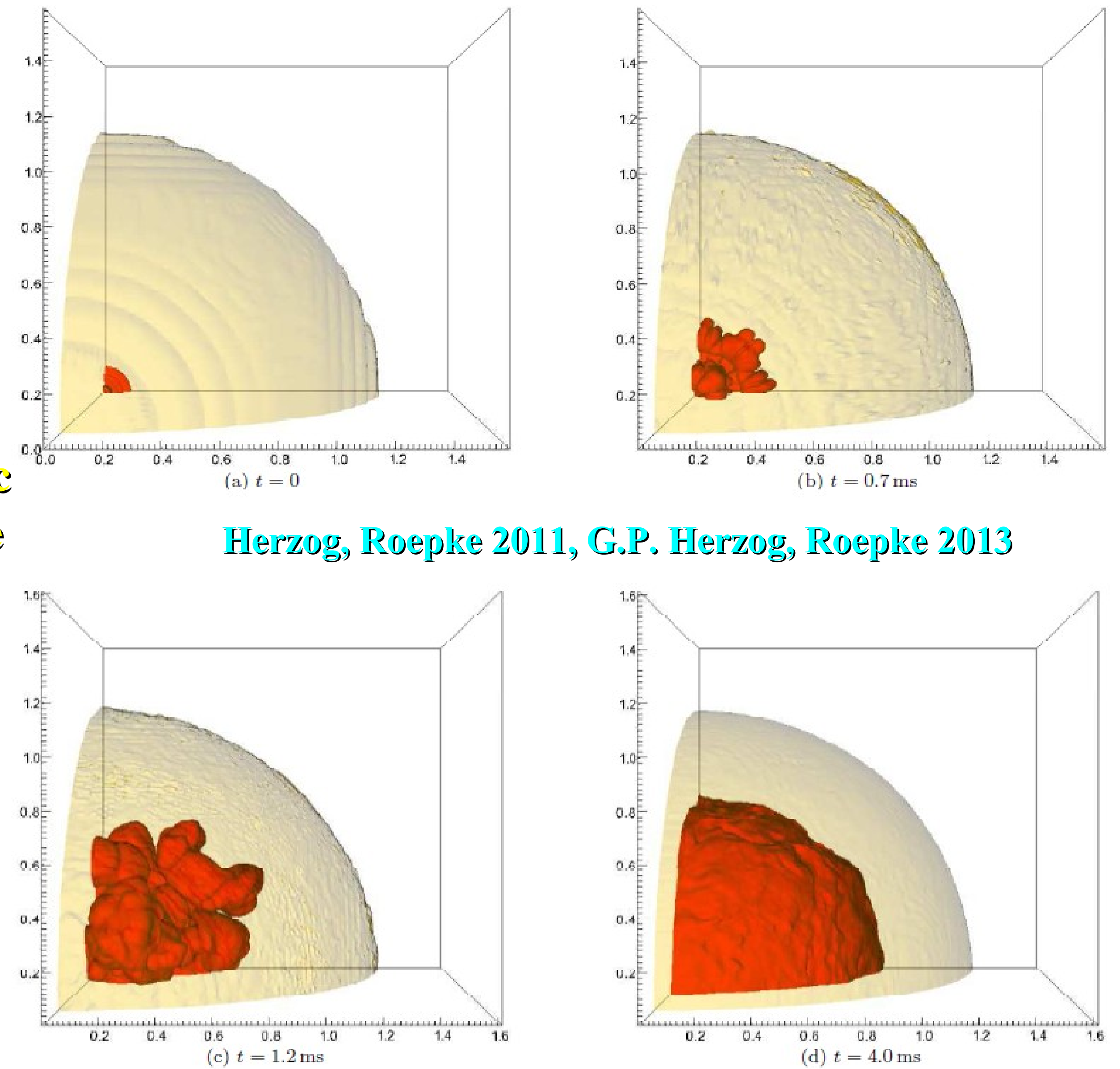
$$X = (e + P)/n_B^2$$

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)

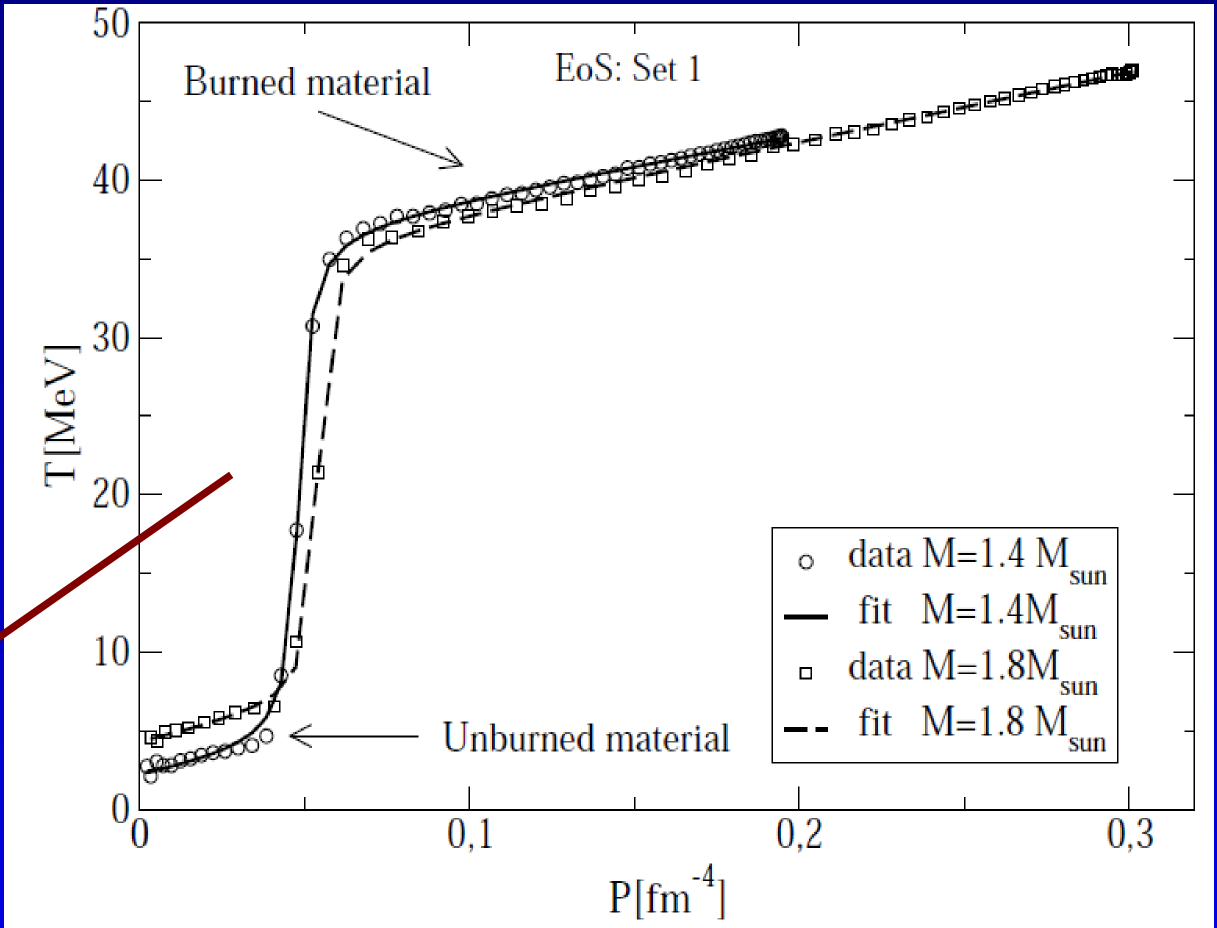


Herzog, Roepke 2011, G.P. Herzog, Roepke 2013

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

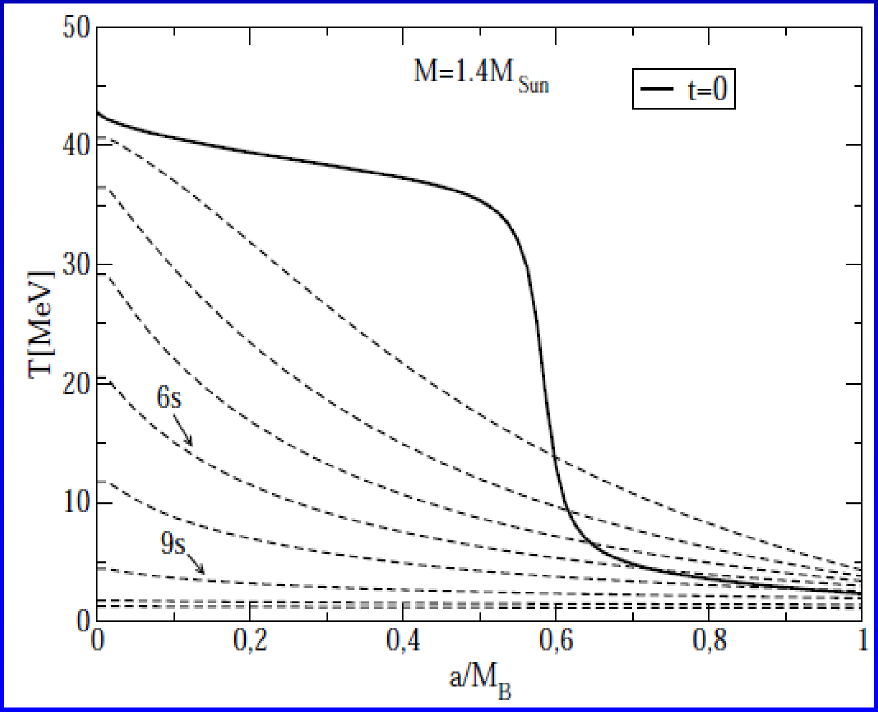
$$\frac{\sigma_S}{V} = \frac{G_F^2 E_\nu^3 \mu_i^2}{5\pi^3}$$

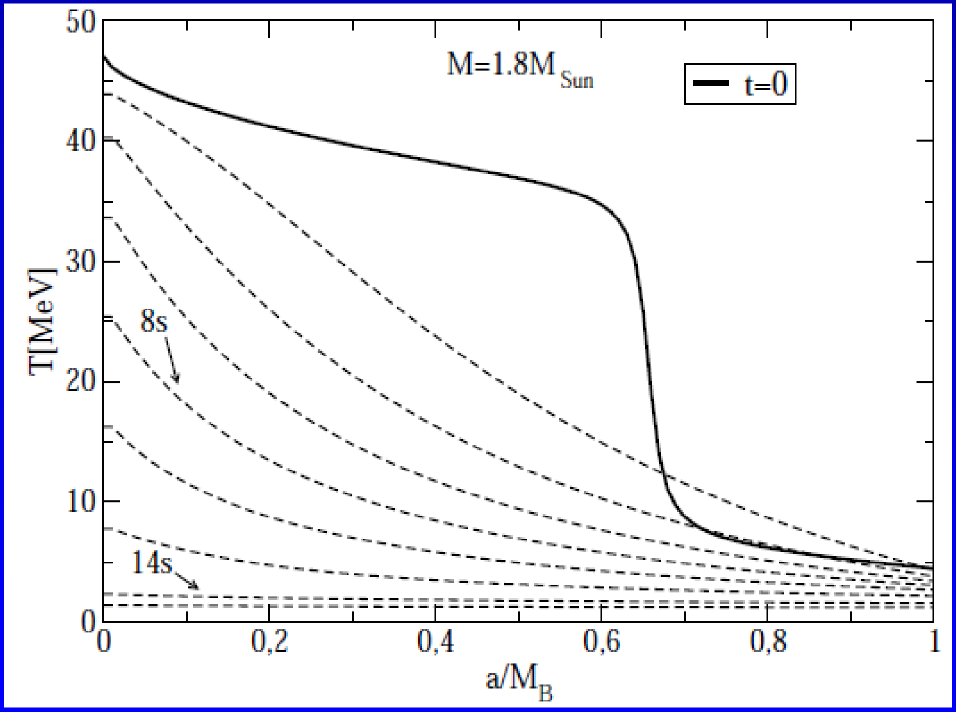
Steiner et al 2001

Expected smaller cooling times with respect to hot neutron stars

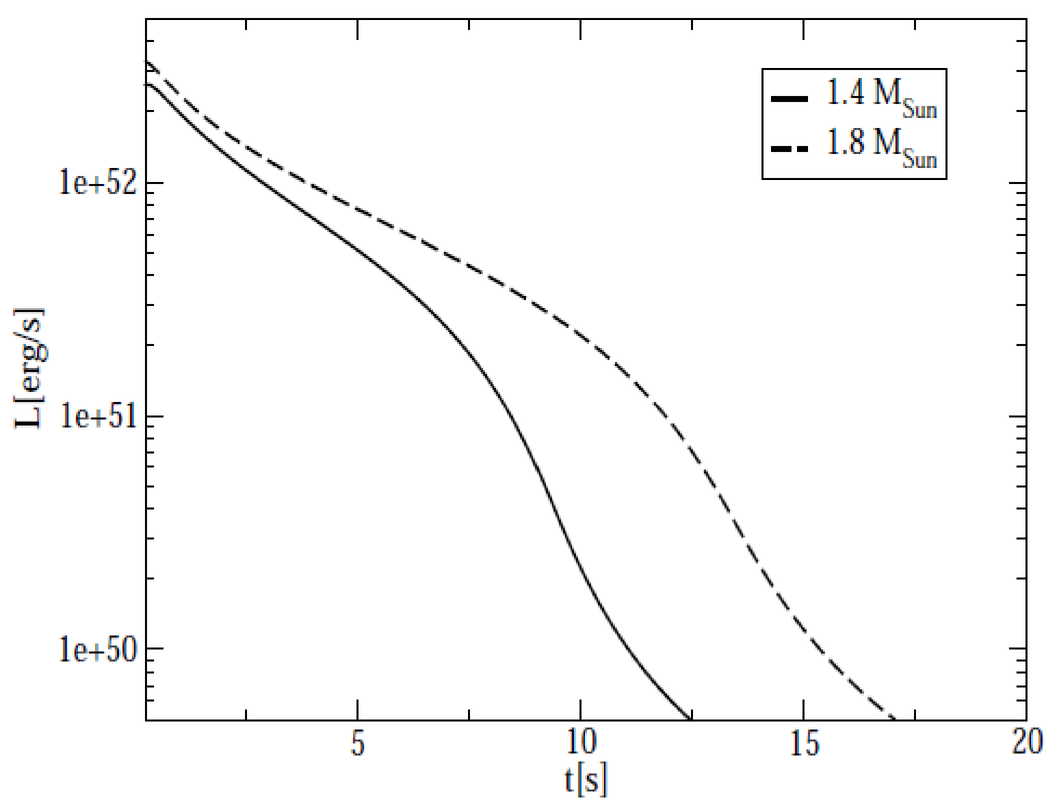
phase	process	λ(T=5 MeV)	λ(T=30 MeV)
Nuclear Matter	$\nu n \to \nu n$	200 m	1 cm
	$\nu_e n \to e^- p$	2 m	4 cm
Unpaired Quarks	$\nu q \to \nu q$	350 m	1.6 m
	$\nu d \to e^- u$	120 m	4 m
CFL	λ_{3B}	100 m	70 cm
	$\nu\phi \to \nu\phi$	>10 km	4 m

Reddy et al 2003





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



Phenomenology 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. 2.4 Msun candidates already exist.

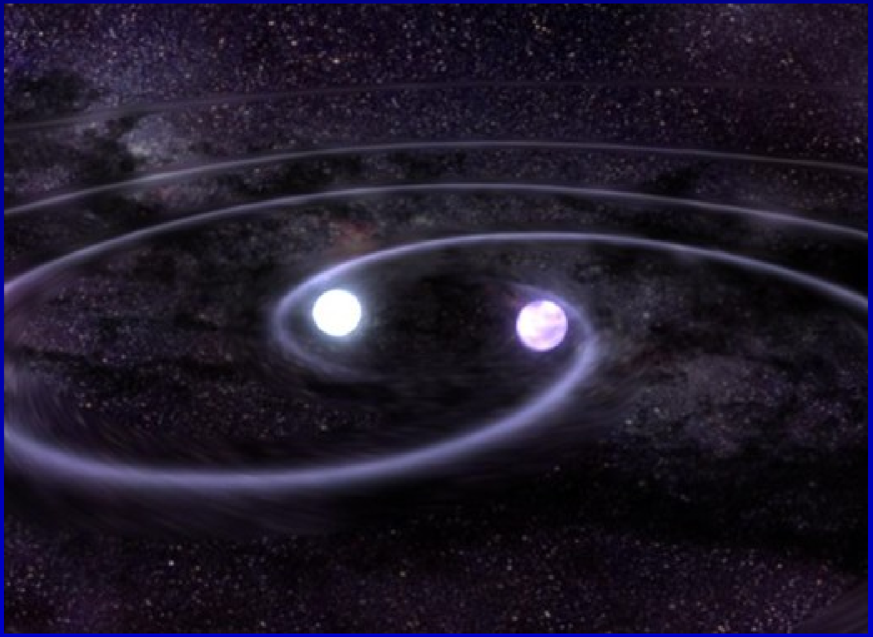
-) Hyperons and delta puzzles

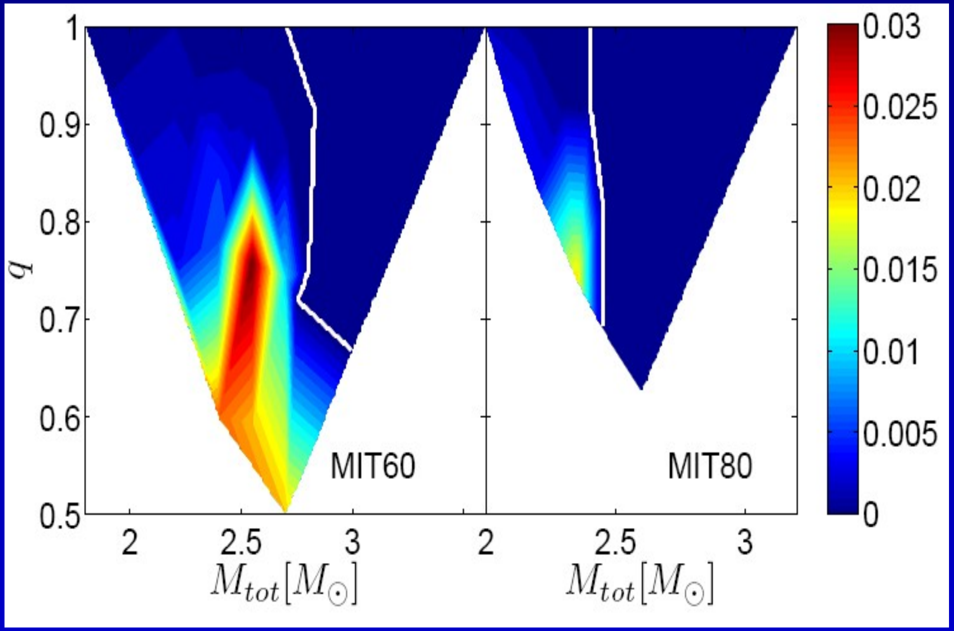
-) NICER mission, with a precision of 1km in radii measurements, could hopefully solve the problem

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

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

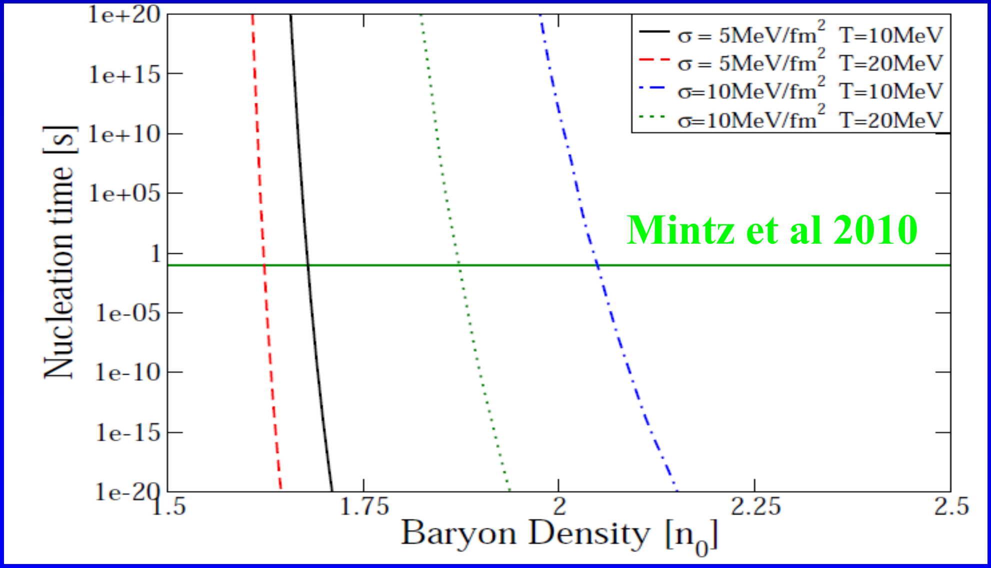
$$\Gamma = T^4 \exp\left[-\frac{16\pi}{3}\frac{\sigma^3}{(\Delta p)^2 T}\right]$$

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

… 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

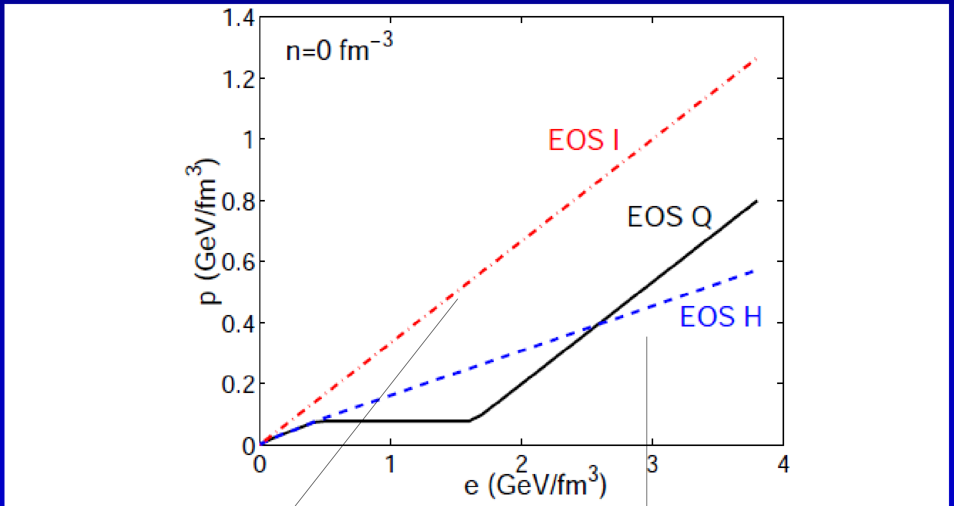


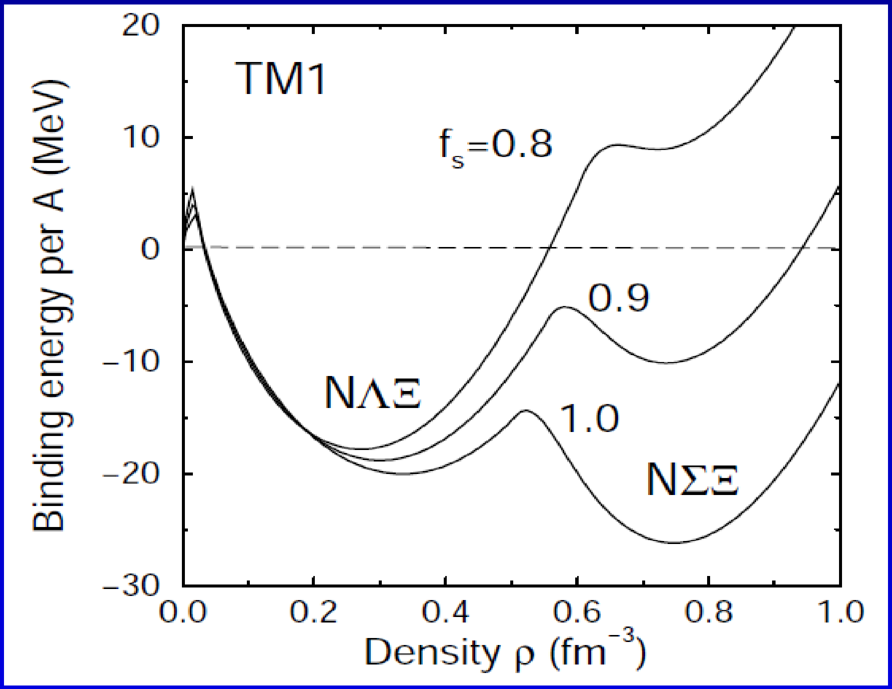
Fig. 1. Equation of state of the Hagedorn resonance gas (EOS H), an ideal gas of massless particles (EOS I) and the Maxwellian connection of those two as discussed in the text (EOS Q). The figure shows the pressure as function or energy density at vanishing net baryon density.

p=e/3 massless quarks

Hadron resonance gas

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)

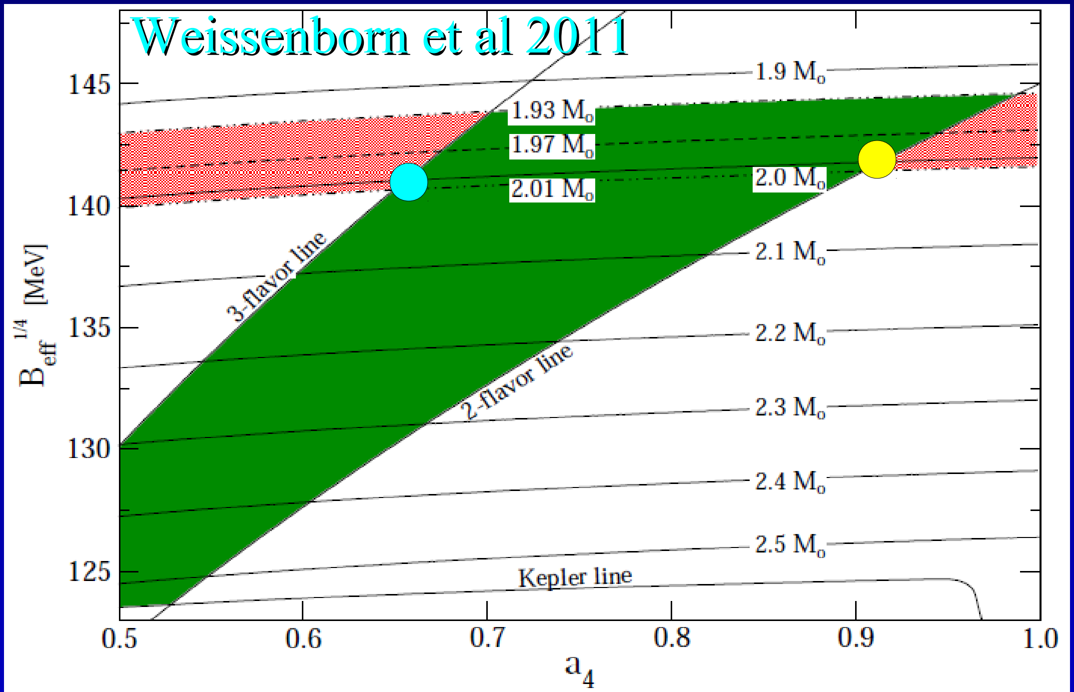
Within a simple parametrization:

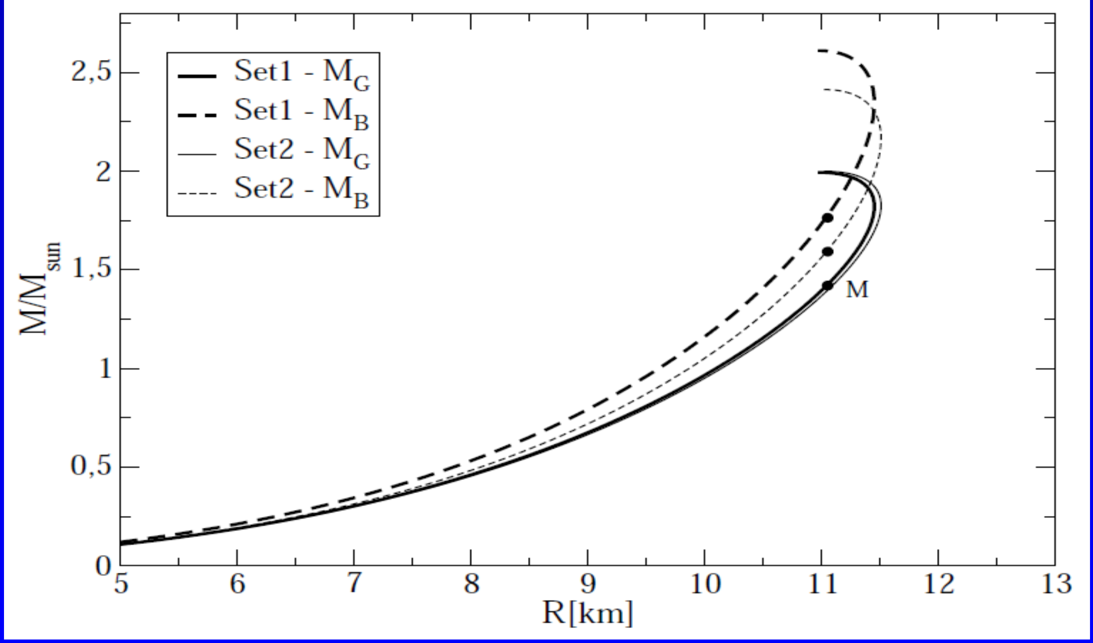
$$\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \frac{3\mu^4}{4\pi^2}(1-a_4) + B_{eff}$$

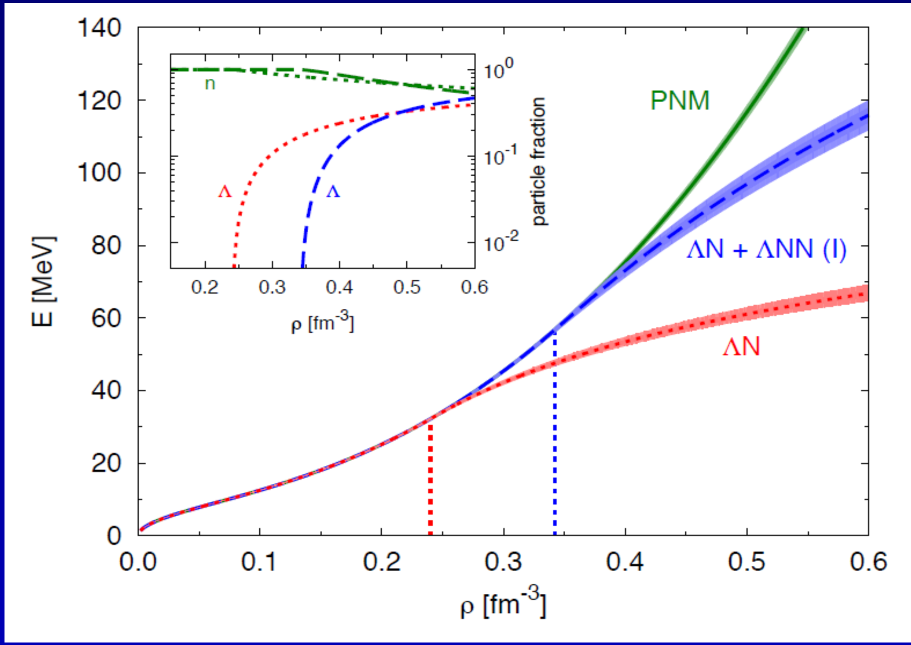
Two EoSs which provide a maximum mass of $2M_{sun}$

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

Different QSs binding energy M_B-M_G







E [MeV]
ρ [fm^{-3}]
PNM
ΛN + ΛNN (I)
ΛN
n
Λ
Λ
particle fraction
ρ [fm^{-3}]