The supranuclear equation of state stiffness (once again...)

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CSQCD V

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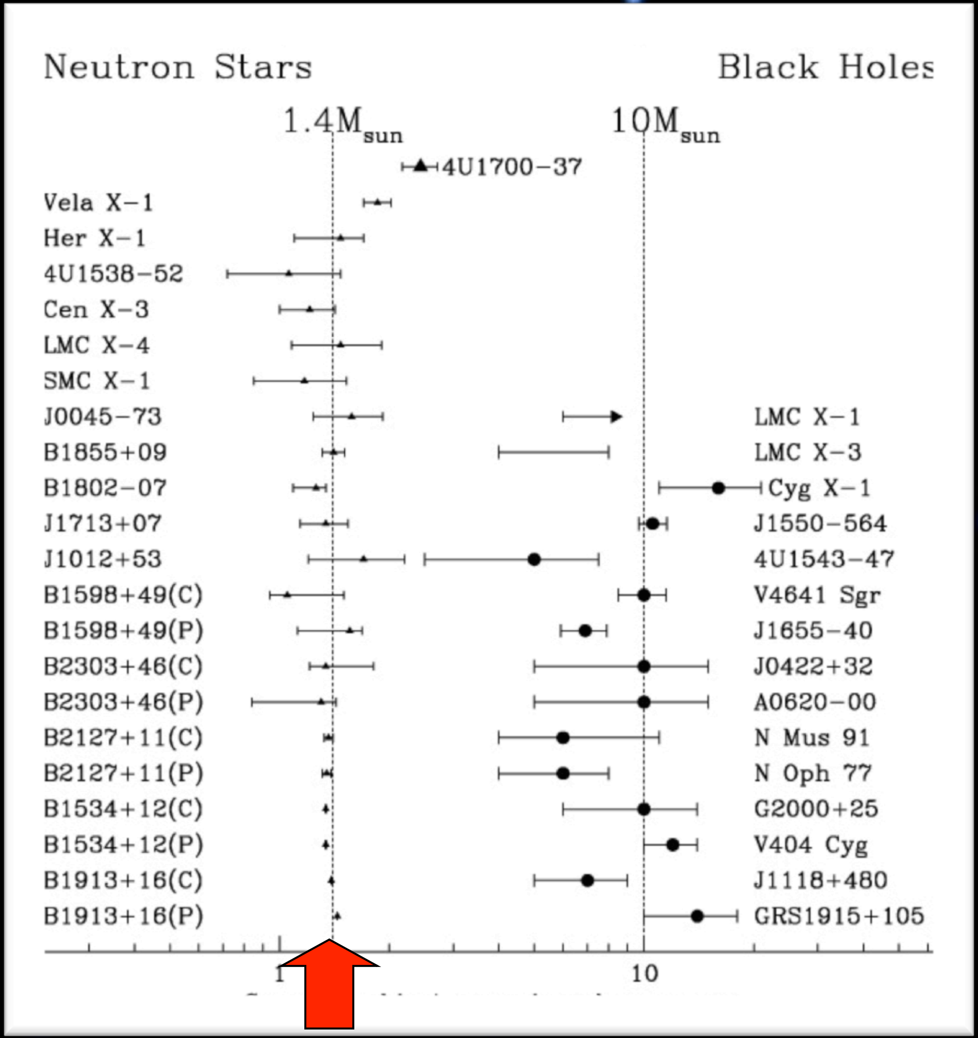
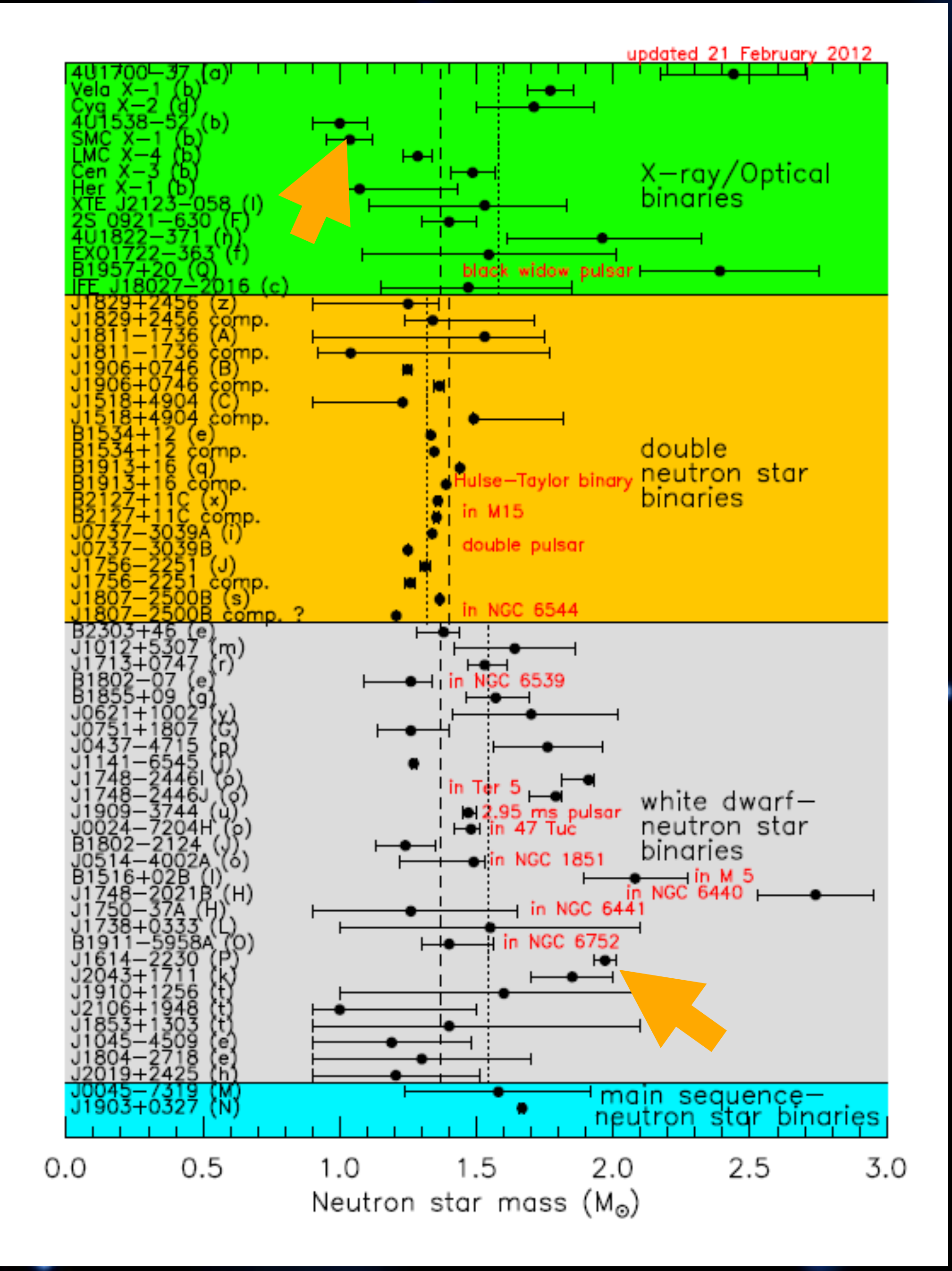
Once upon a time the idea of a single mass scale was firmly rooted in the community, and a 1.4 $M_{\odot}$ dubbed "canonical"



Consistent with 1.4 $M_{\odot}$

Figure from Clark et al. A&A 392, 909 (2002)

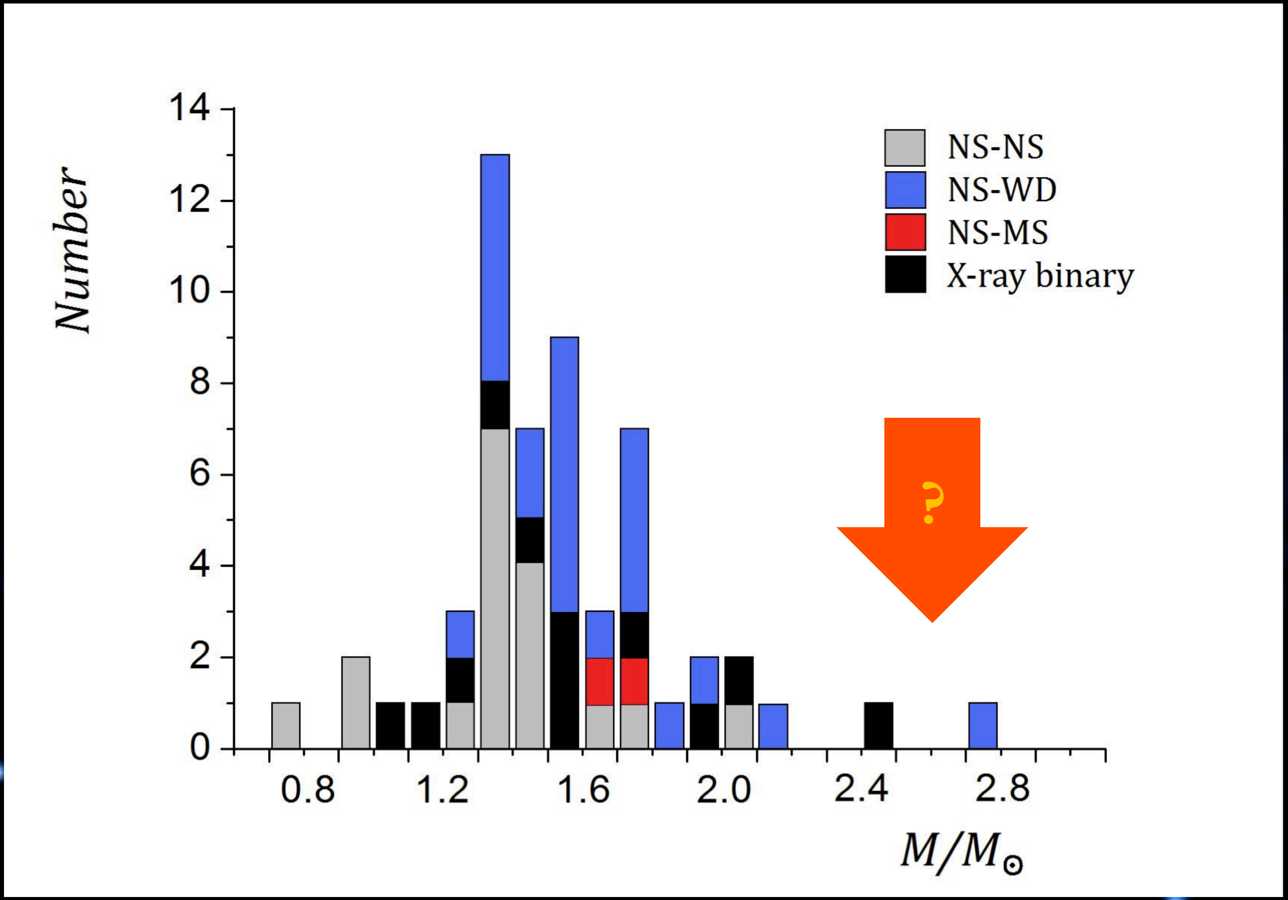


However, the newest evidence points towards a *much wider* range of masses

Sample compiled by Lattimer et al 2015, available at

http://www.stellarcollapse.org/nsmasses

Updated neutron star mass histogram



Valentim, Rangel & Horvath (MNRAS 414, 1427, 2011) :
Evidence for (at least) two mass scales
Within a double gaussian scenario peaks at 1.37 and 1.73 M_O

Other works finding the same pattern:

Zhang et al. A&A 527, A83, 2011
Özel et al., ApJ 757, 55, 2012 (1.33 and 1.48 M_O)
Kiziltan, Kottas & Thorsett, arXiv:1011.4291 (1.35 and 1.5 M_O)

Latest news:

Özel et al (latest data): 1.39 and 1.8 M_O narrow and wide peaks.
Second peak very populated
Inferred maximum mass ~ 2.15 M_O

Confirmation of the bimodality, exact shape not sure (power-law?)

Moreover...
There is strong evidence for massively born pulsars (van den Heuvel, Tauris...)

HMXB Vela X1 (M_{NS} = 2.1 (1) M_O , Falanga et al. 2015)
4U 1700-37 (M_{NS} = 2.4 (3) M_O , Kaper et al. 2016)

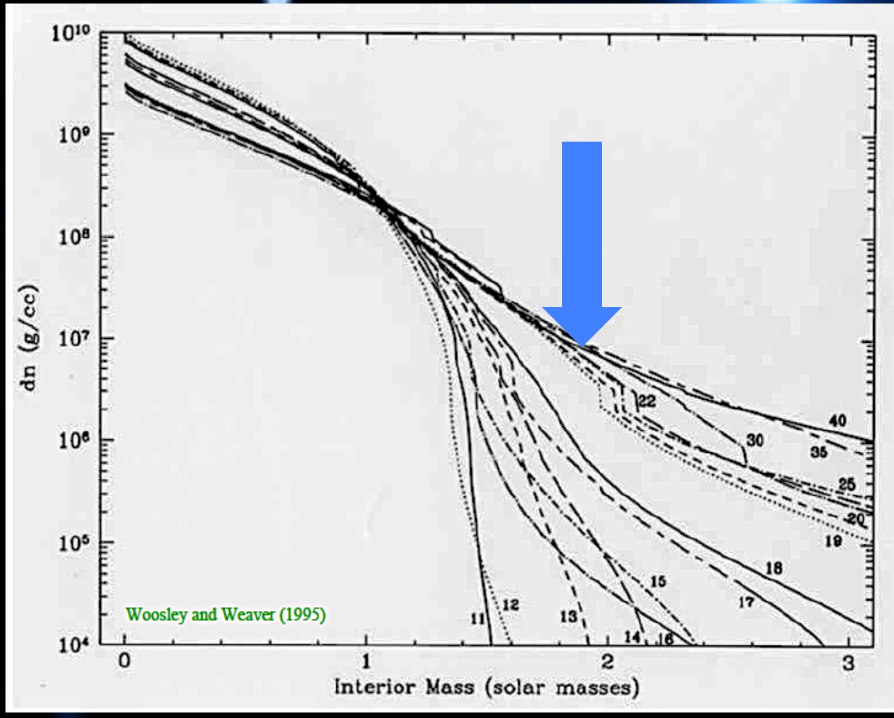
- Short evolutionary timescale of the donor ~ 10 Myr
- Eddington-limited accretion < 10^{-8} M_O/yr

M_{acc} < 0.1 M_O !!! HOW SO?

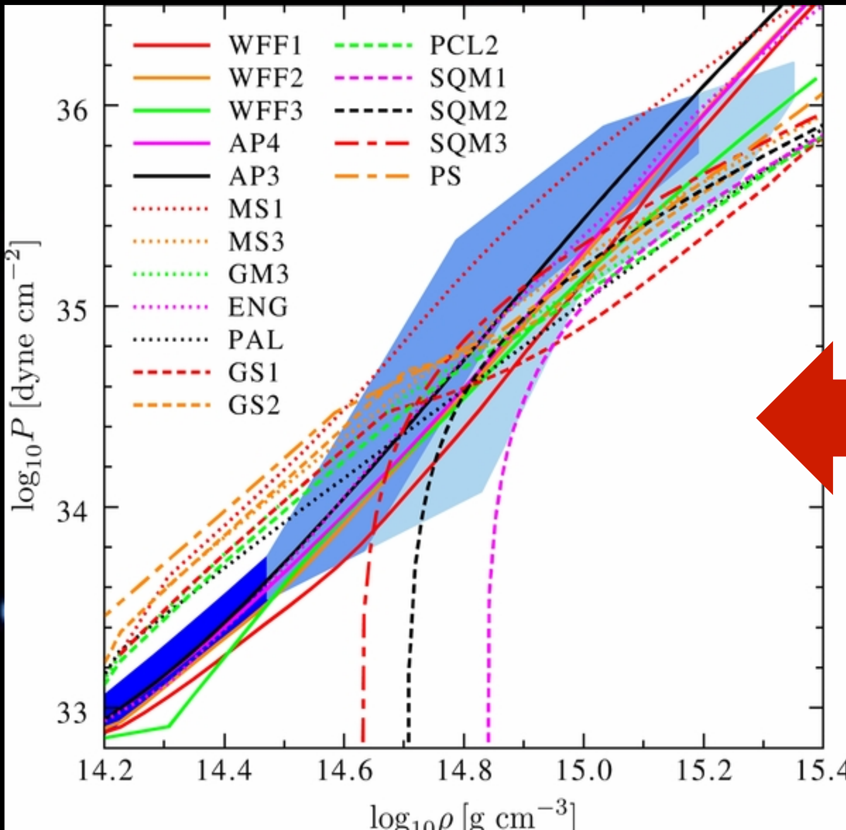
Around ~ 18 M_O progenitors develop massive > 1.8-2 M_O cores because of the

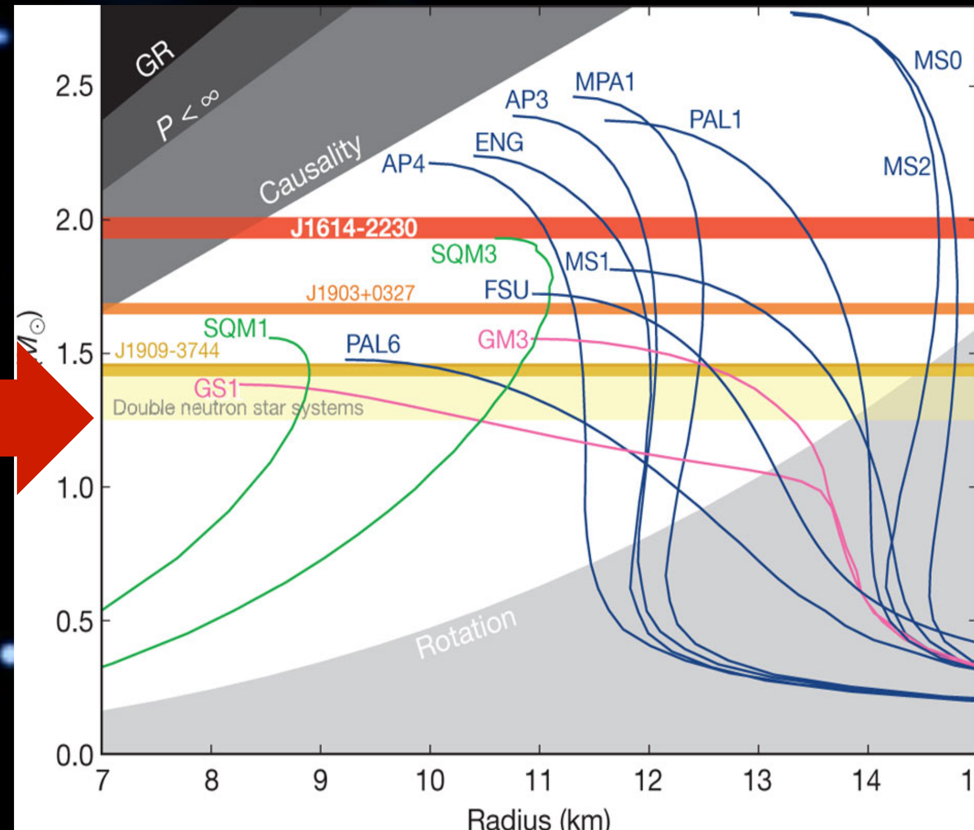
$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$

If they explode, massive NSs result

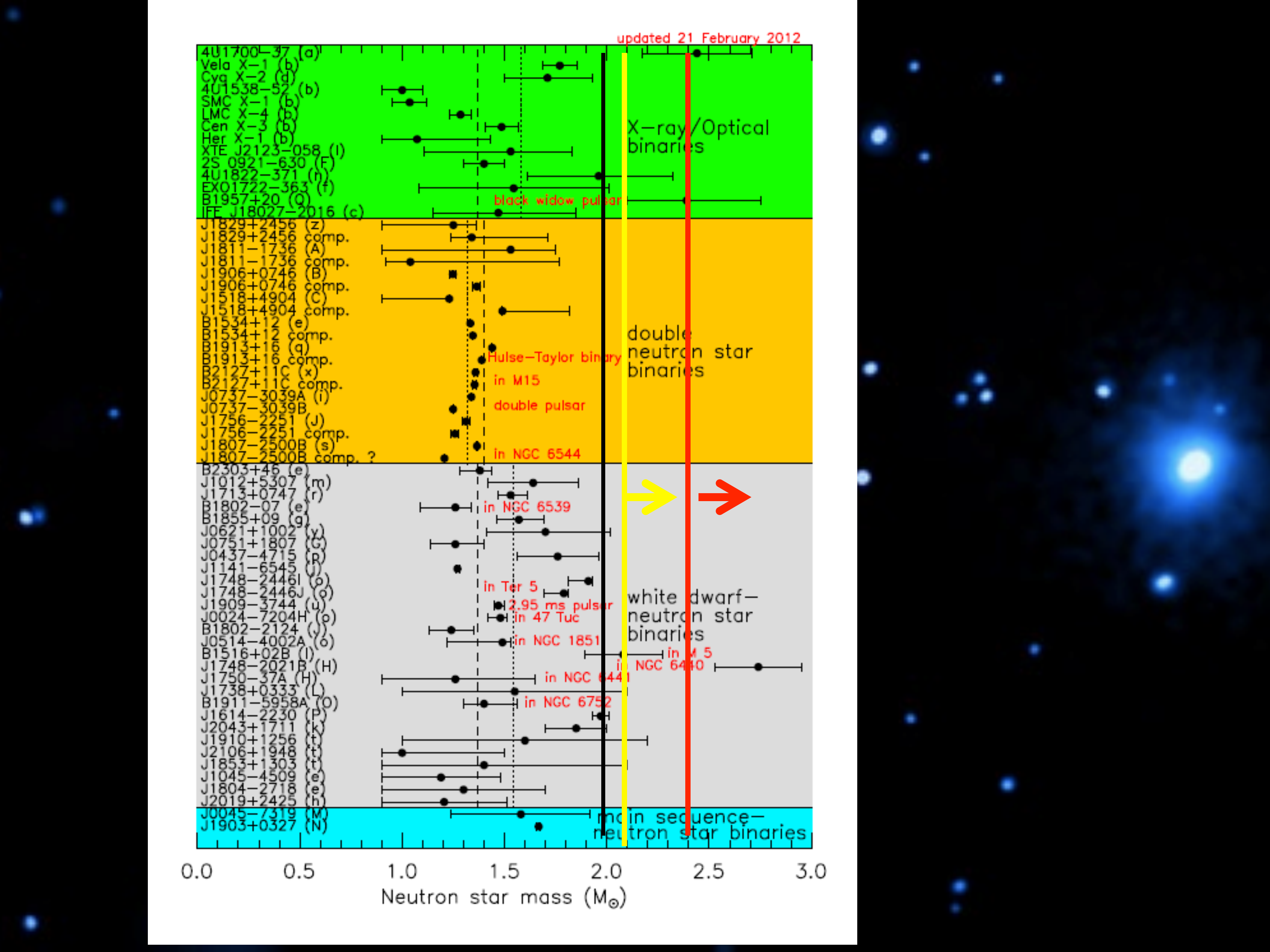


Dense matter may be considered as "known" up to ~ 2 ρ_0, but…





Degrees of freedom (i.e. hyperons, quarks, etc)
Interactions (including 3-body forces)
Medium effects
…


updated 21 February 2012
4U1700−37 (a)
Vela X−1 (b)
Cyg X−2 (d)
4U1538−52 (b)
SMC X−1 (b)
LMC X−4 (b)
Cen X−3 (b)
Her X−1 (b)
XTE J2123−058 (l)
2S 0921−630 (F)
4U1822−371 (n)
EXO1722−363 (f)
B1957+20 (Q)
IFE J18027−2016 (c)
black widow pulsar
X−ray/Optical binaries
J1829+2456 (z)
J1829+2456 comp.
J1811−1736 (A)
J1811−1736 comp.
J1906+0746 (B)
J1906+0746 comp.
J1518+4904 (C)
J1518+4904 comp.
B1534+12 (e)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
B2127+11C (x)
B2127+11C comp.
J0737−3039A (i)
J0737−3039B
J1756−2251 (J)
J1756−2251 comp.
J1807−2500B (s)
J1807−2500B comp. ?
Hulse−Taylor binary
in M15
double pulsar
in NGC 6544
double neutron star binaries
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802−07 (e)
B1855+09 (g)
J0621+1002 (y)
J0751+1807 (G)
J0437−4715 (R)
J1141−6545 (j)
J1748−2446I (o)
J1748−2446J (o)
J1909−3744 (u)
J0024−7204H (o)
B1802−2124 (j)
J0514−4002A (o)
B1516+02B (l)
J1748−2021B (H)
J1750−37A (H)
J1738+0333 (L)
B1911−5958A (O)
J1614−2230 (P)
J2043+1711 (k)
J1910+1256 (t)
J2106+1948 (t)
J1853+1303 (t)
J1045−4509 (e)
J1804−2718 (e)
J2019+2425 (h)
in NGC 6539
in Ter 5
2.95 ms pulsar
in 47 Tuc
in NGC 1851
in M 5
in NGC 6440
in NGC 6441
in NGC 6752
white dwarf−neutron star binaries
J0045−7319 (M)
J1903+0327 (N)
main sequence−neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)


Back to 2006 !
THE TIME TUNNEL

What do exotic equations of state have to offer?

J.E. Horvath

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Isolated Neutron Stars

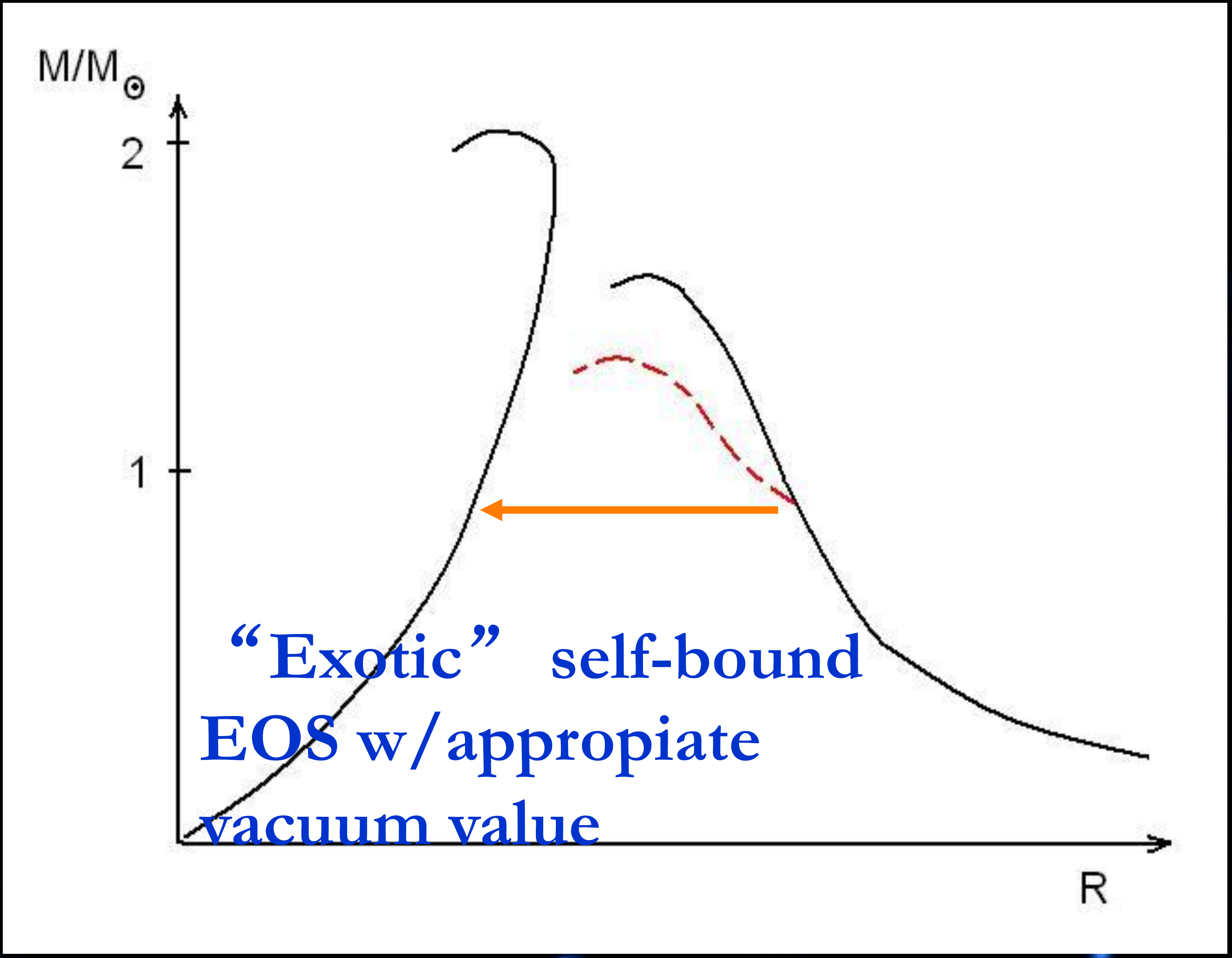
London, April 24-28 2006

Role of hyperons in hadronic matter : included in some NR form, they tend to soften the EOS. Threshold at 2-3 ρ_0

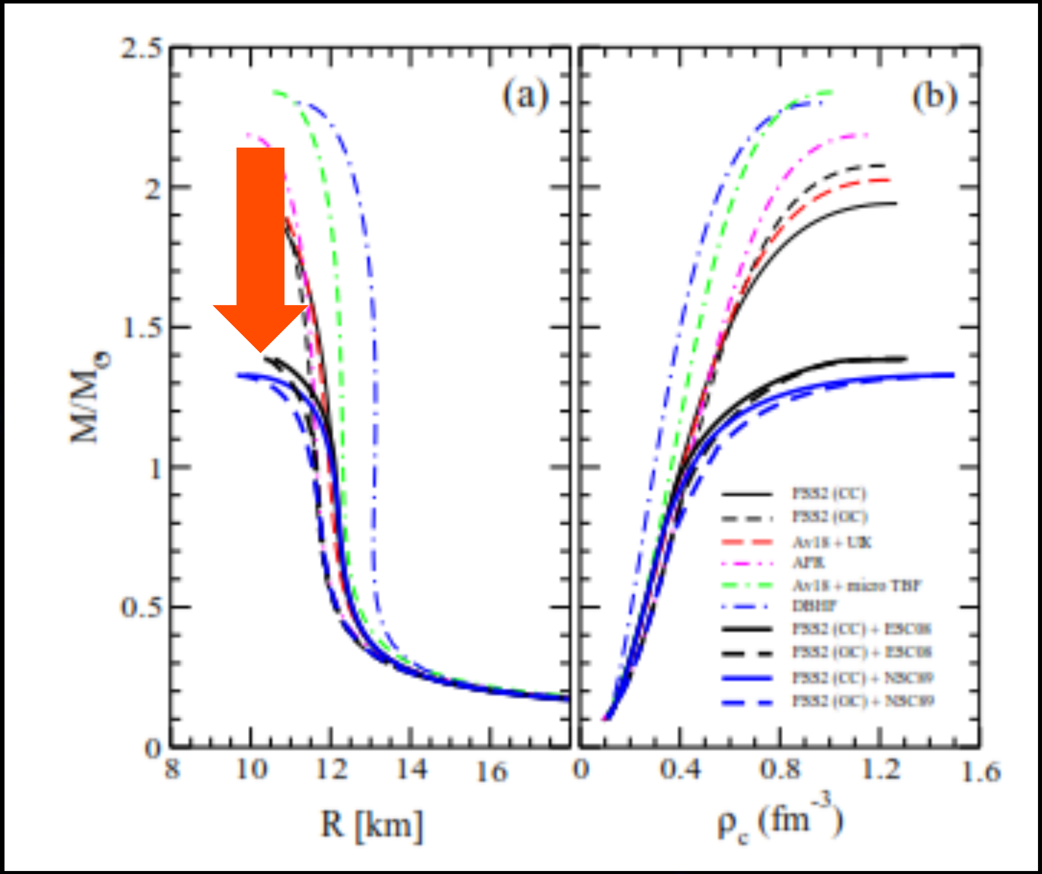
Interactions of hyperons with p,n still uncertain
Generally H-n and H-p interactions are **not** included in the calculations

Existing EOS which behave quite stiffly either

a)Do not include hyperons
b)Include hyperons but use mean-field theories (e.g. Walecka-type) instead of a microscopic approach


M/M⊙
2
1
R
“Exotic” self-bound
EOS w/appropiate
vacuum value

Hyperons are nasty beasts…



(Baldo's talk)

Some of the hyperon main problems

What is really included and what is not in hyperon-nucleon interactions ? (Pederiva)

In particular 3-body forces can be "tuned" to give more repulsion $C_T < 1$

Computing-measuring hypernuclei binding energies , computing is not difficult but the input must be accurate. Experiments are scarce and proba only a limited range

For infinite matter there are less constraints than for the nuclear matter case (saturation, K...)

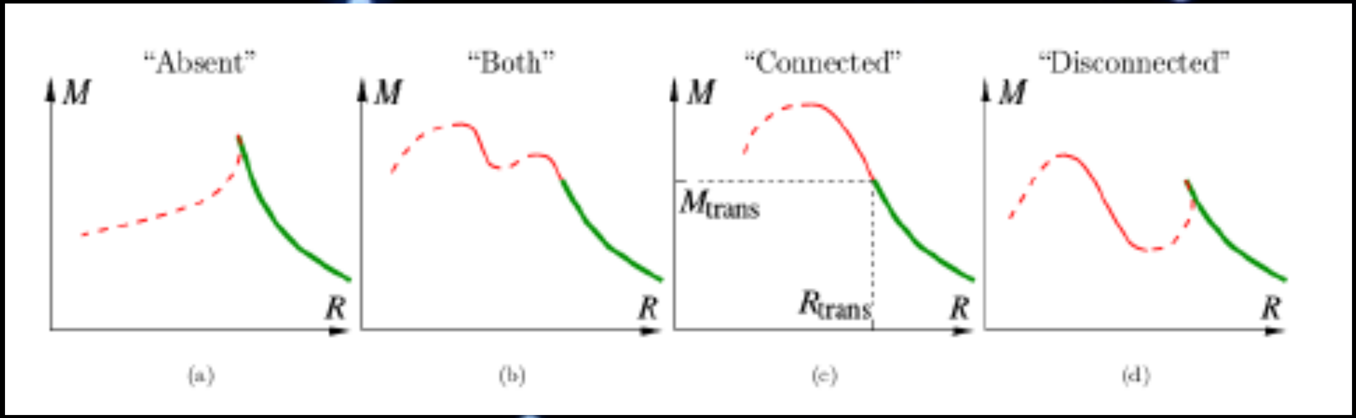
Constructing hybrid stars with hyperons

(R.A. De Souza Thesis, May 2016)

GR is THE theory and Brane Worlds are irrelevant

(Lugones-Arbanil)

There is a single sequence of stars (but see Drago's talk)



(Alford et al.)

$\sigma - \omega - \rho - \delta - \phi$ model (Gomes et al. 2015) baryonic octed + mesons

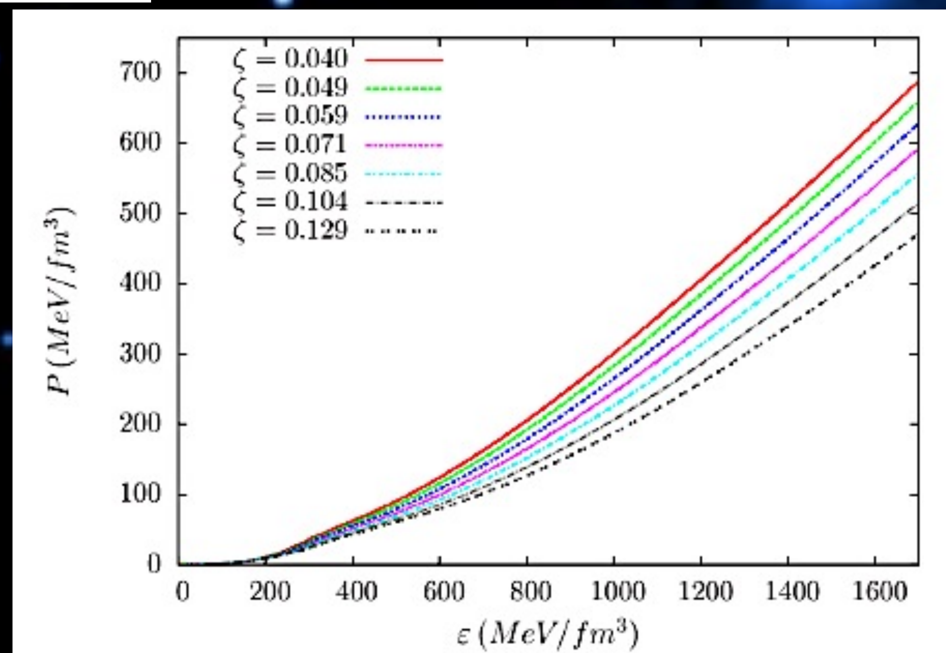
$$\mathcal{L} = \sum_b \overline{\psi}_b \Big[\gamma_\mu \Big(i\partial^\mu - g^*_{\omega b \xi}\omega^\mu - g^*_{\phi b \kappa}\phi^\mu - \frac{1}{2} g^*_{\varrho b \eta} \tau . \varrho^\mu \Big) - \Big(1 + \frac{g_{\sigma b}\sigma + g_{\sigma^* b}\sigma^* + \frac{1}{2} g_{\delta b}\tau . \delta}{\zeta m_b} \Big)^{-\zeta} m_b \Big] \psi_b$$
$$+ \Big(\frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - m^2_\sigma \sigma^2 \Big) + \Big(\frac{1}{2}\partial_\mu \sigma^* \partial^\mu \sigma^* - m^2_{\sigma^*} \sigma^{*2} \Big)$$
$$+ \frac{1}{2}\Big(-\frac{1}{2}\omega_{\mu\nu}\omega^{\mu\nu} + m^2_\omega \omega_\mu \omega^\mu \Big) + \frac{1}{2}\Big(-\frac{1}{2}\phi_{\mu\nu}\phi^{\mu\nu} + m^2_\phi \phi_\mu \phi^\mu \Big)$$
$$+ \frac{1}{2}\Big(-\frac{1}{2}\varrho_{\mu\nu} . \varrho^{\mu\nu} + m^2_\varrho \varrho_\mu . \varrho^\mu \Big) + \Big(\frac{1}{2}\partial_\mu \delta . \partial^\mu \delta - m^2_\delta \delta^2 \Big)$$
$$+ \sum_l \overline{\psi}_l \gamma_\mu (i\partial^\mu - m_l) \psi_l .$$

$$g^*_{\omega b \xi} \equiv m^*_{\xi b} g_{\omega b}, \quad g^*_{\varrho b \kappa} \equiv m^*_{\kappa b} g_{\varrho b}, \quad g^*_{\phi b \eta} \equiv m^*_{\eta b} g_{\phi b},$$

Meson+baryon

$$m^*_{\lambda b} \equiv \Big(1 + \frac{g_{\sigma b}\sigma + g_{\sigma^* b}\sigma^* + \frac{1}{2} g_{\delta b}\tau . \delta}{\lambda m_b} \Big)^{-\lambda} \quad \lambda = \xi, \kappa, \eta, \zeta$$

Derivative coupling "sums up" many body forces



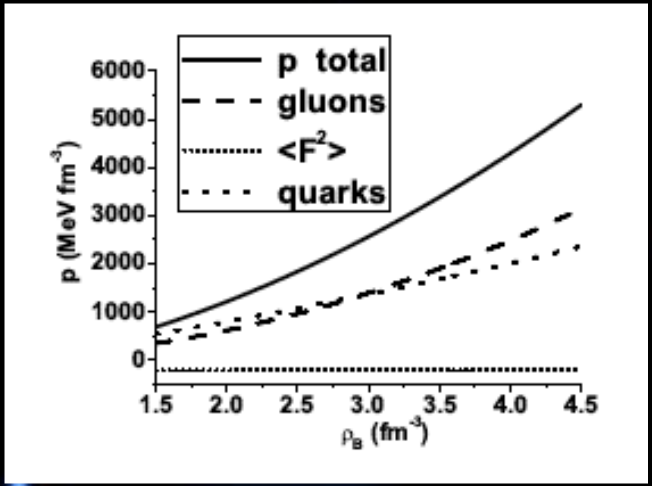
Mean field quark matter (Fogaca & Navarra 2011, Franzon et al.2013)

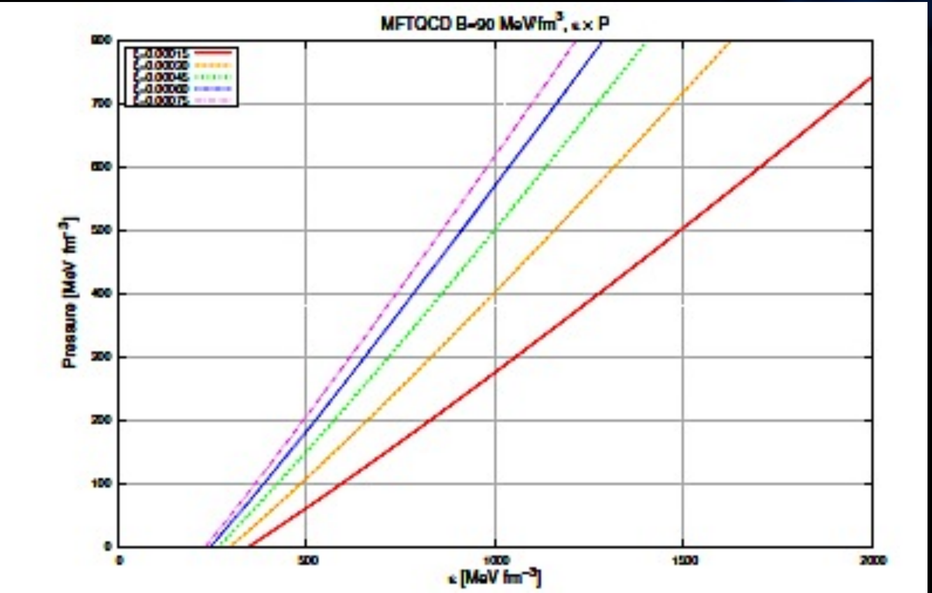
$$\epsilon = \left(\frac{27g^2}{16m_G^2}\right)\rho_B{}^2 + B_{QCD}$$
$$+ \sum_{i=u,d,s} 3\frac{\gamma_Q}{2\pi^2}\left\{\frac{k_i{}^3\sqrt{k_i{}^2+m_i{}^2}}{4} + \frac{m_i{}^2 k_i\sqrt{k_i{}^2+m_i{}^2}}{8} - \frac{m_i{}^4}{8}ln\left[k_i+\sqrt{k_i{}^2+m_i{}^2}\right] + \frac{m_i{}^4}{16}ln(m_i{}^2)\right\}$$
$$+ \frac{\gamma_e}{2\pi^2}\left\{\frac{k_e{}^3\sqrt{k_e{}^2+m_e{}^2}}{4} + \frac{m_e{}^2 k_e\sqrt{k_e{}^2+m_e{}^2}}{8} - \frac{m_e{}^4}{8}ln\left[k_i+\sqrt{k_e{}^2+m_e{}^2}\right] + \frac{m_e{}^4}{16}ln(m_e{}^2)\right\}$$

$$p = \left(\frac{27g^2}{16m_G^2}\right)\rho_B{}^2 - B_{QCD}$$
$$+ \sum_{i=u,d,s} \frac{\gamma_Q}{2\pi^2}\left\{\frac{k_i{}^3\sqrt{k_i{}^2+m_i{}^2}}{4} - \frac{3m_i{}^2 k_i\sqrt{k_i{}^2+m_i{}^2}}{8} + \frac{3m_i{}^4}{8}ln\left[k_i+\sqrt{k_i{}^2+m_i{}^2}\right] - \frac{3m_i{}^4}{16}ln(m_i{}^2)\right\}$$
$$+ \frac{\gamma_e}{6\pi^2}\left\{\frac{k_e{}^3\sqrt{k_e{}^2+m_e{}^2}}{4} - \frac{3m_e{}^2 k_e\sqrt{k_e{}^2+m_e{}^2}}{8} + \frac{3m_e{}^4}{8}ln\left[k_e+\sqrt{k_e{}^2+m_e{}^2}\right] - \frac{3m_e{}^4}{16}ln(m_e{}^2)\right\},$$

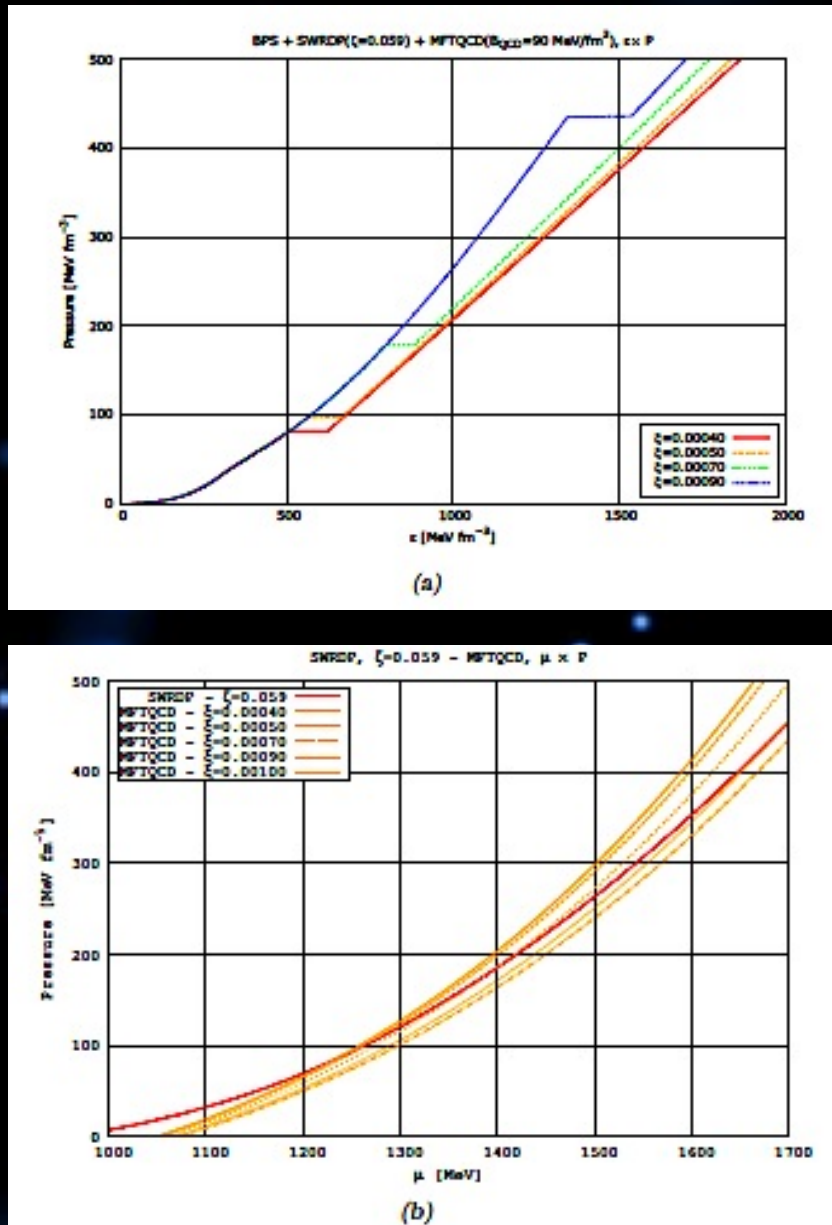
$$B_{QCD} = \frac{9}{128}\phi_0^4 = \langle\frac{1}{4}F^{a\mu\nu}F^a_{\mu\nu}\rangle$$

Related to the MIT bag (vacuum+condensate)





Constructing phase transitions : local charge conservation (Maxwell)



Study of the interfase makes unlikely (not impossible) a large mixed phase Yasutake et al. 2016

Results

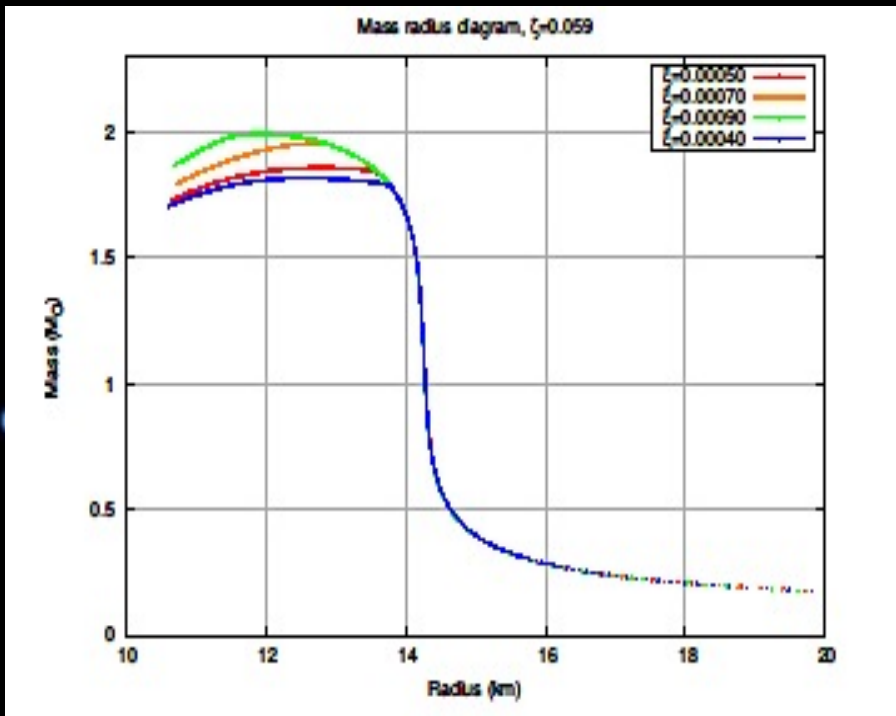


Tabela 7.1 - Massas máximas das estrelas no modelo BPS+SWRDP+MFTQCD, com as variações de ζ, ξ e $B_{QCD} = 90\ MeV/fm^3$.

ζ	ξ	$M_{max}/M_\odot$	Raio km	Densidade central MeV/fm^3	Tipo
0.040	0.00050	1.84	12.82	936	Híbrida
	0.00070	1.95	13.81	698.8	Híbrida
	0.00090	2.08	13.42	815.8	Híbrida
	0.00100	2.13	13.06	936.7	Híbrida
0.049	0.00040	1.81	12.53	1013.2	Híbrida
	0.00050	1.85	12.87	919	Híbrida
	0.00070	1.96	13.28	817.9	Híbrida
	0.00090	2.06	12.72	1014.6	Híbrida
0.059	0.00040	1.82	12.55	999	Híbrida
	0.00050	1.86	12.79	933.9	Híbrida
	0.00070	1.96	12.71	970.45	Híbrida
	0.00090	1.99	11.94	1167.9	Hadrônica
0.071	0.00040	1.83	12.45	1013.2	Híbrida
	0.00050	1.87	12.43	1024.8	Híbrida
	0.00070	1.91	11.66	1245.8	Hadrônica
0.085	0.00040	1.82	11.76	1272.9	Híbrida

The Hyperon Puzzle in Neutron Stars

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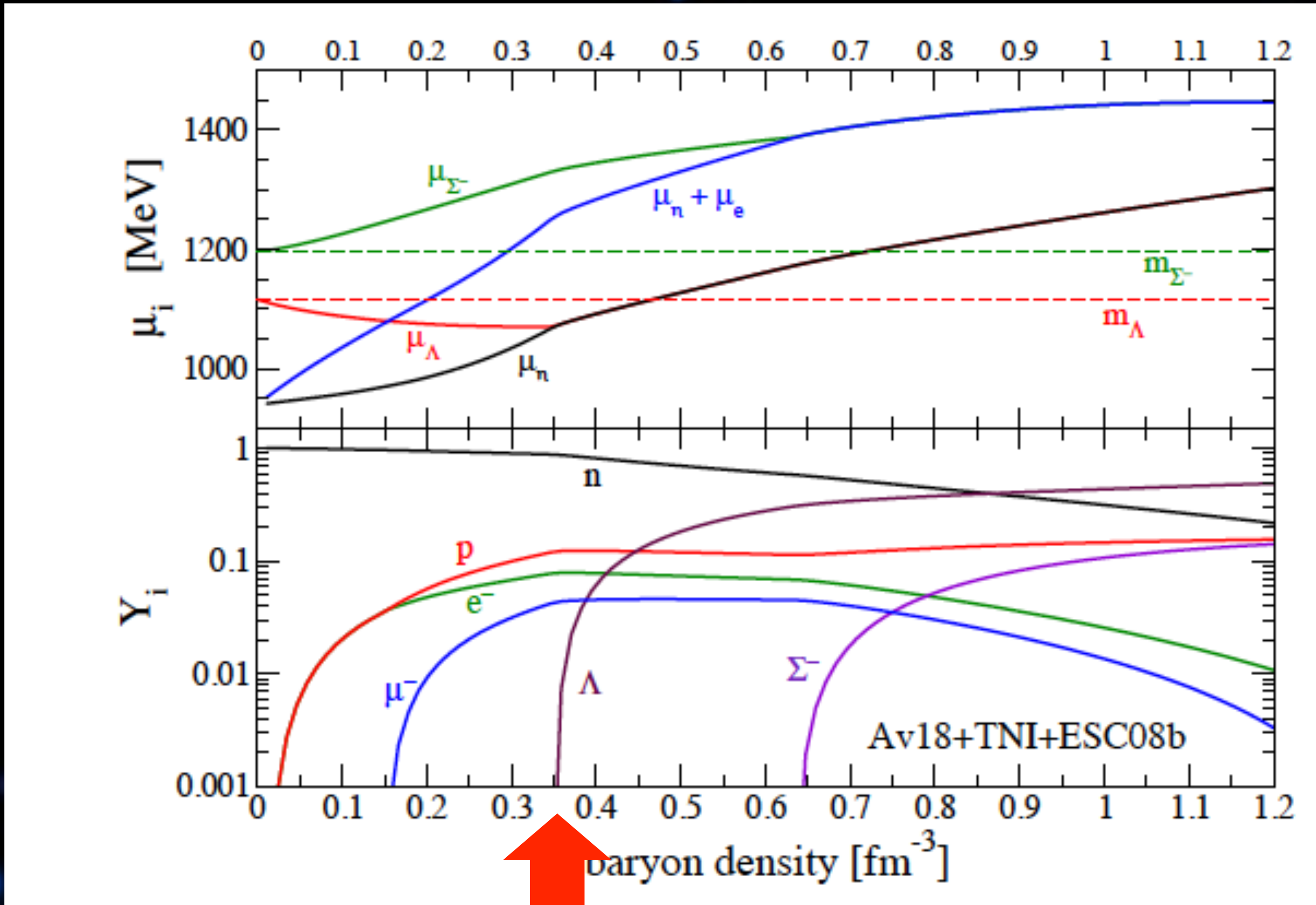
E-mail: ignazio.bombaci@unipi.it

arXiv:1601.05339



What do high masses mean: the "hyperon puzzle"

Hyperons soften the equation of state, do they?

Hyperon Puzzle: Hints from Quantum Monte Carlo Calculations

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The onset of hyperons in the core of neutron stars and the consequent softening of the equation of state have been questioned for a long time. Controversial theoretical predictions and recent astrophysical observations of neutron stars are the grounds for the so-called *hyperon puzzle*. We calculate the equation of state and the neutron star mass-radius relation of an infinite systems of neutrons and Λ particles by using the auxiliary field diffusion Monte Carlo algorithm. We find that the three-body hyperon-nucleon interaction plays a fundamental role in the softening of the equation of state and for the consequent reduction of the predicted maximum mass. We have considered two different models of three-body force that successfully describe the binding energy of medium mass hypernuclei. Our results indicate that they give dramatically different results on the maximum mass of neutron stars, not necessarily incompatible with the recent observation of very massive neutron stars. We conclude that stronger constraints on the hyperon-neutron force are necessary in order to properly assess the role of hyperons in neutron stars.

Can NS *avoid* the presence of hyperons?
(the return of "pure neutrons")

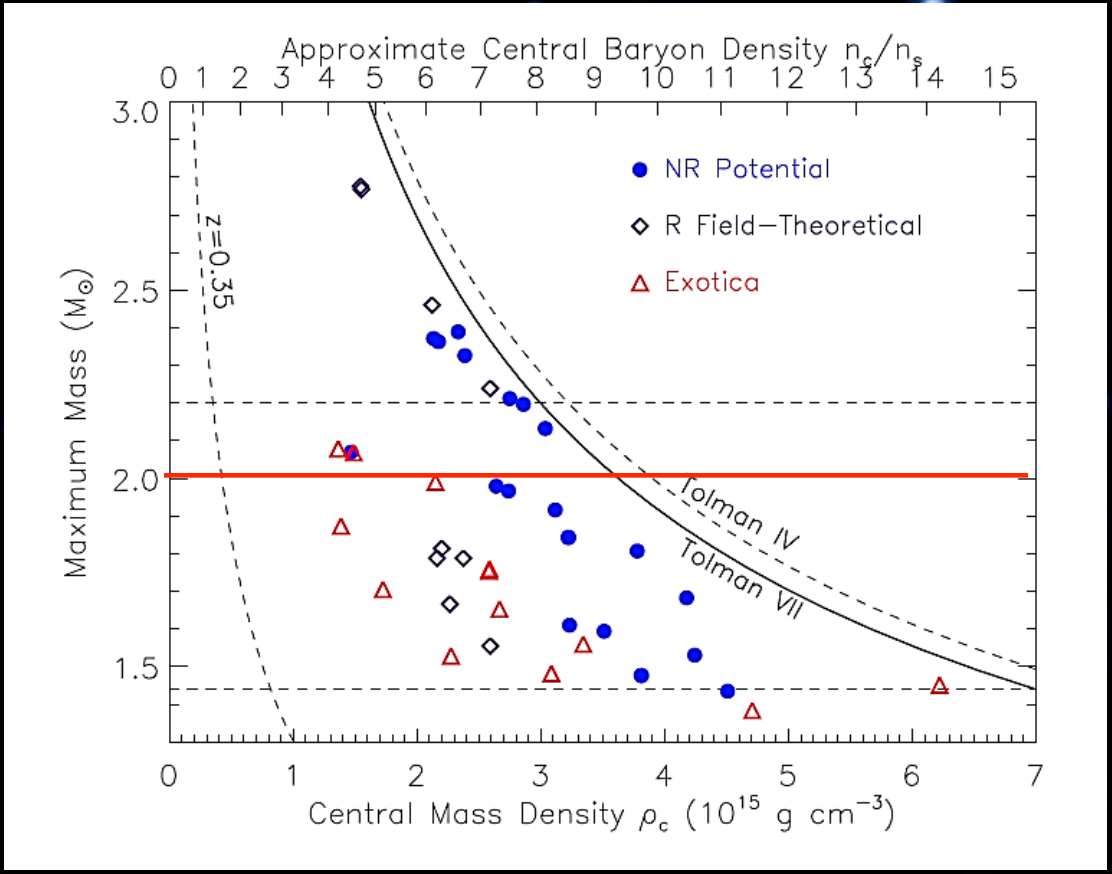
Conclusions

- Stiff equations of state are needed to hold $M > 2\ M_O$ neutron stars (some born as such) . Moreover, we may have to go substantially higher than $2\ M_{O}$, and we may approach the Rhoads-Ruffini limit (?)

- One possible solution is that hyperons do NOT appear in NS. An alternative one is that all NS are strange stars (Lonardoni et al.!)

- If hyperons are present, they must be stiffness associated to them. However, we do not really know where does it come from. Parametrizations and fundamental approaches must be compared carefully

- There is little, if any, room for hybrid stars if hyperon matter is present and stiff. Quarks become an academic problem for NS



Largest observed mass → upper limit to the actual central density in Nature (Lattimer & Prakash 2004)

Central densities are not very large ! (model-independent)