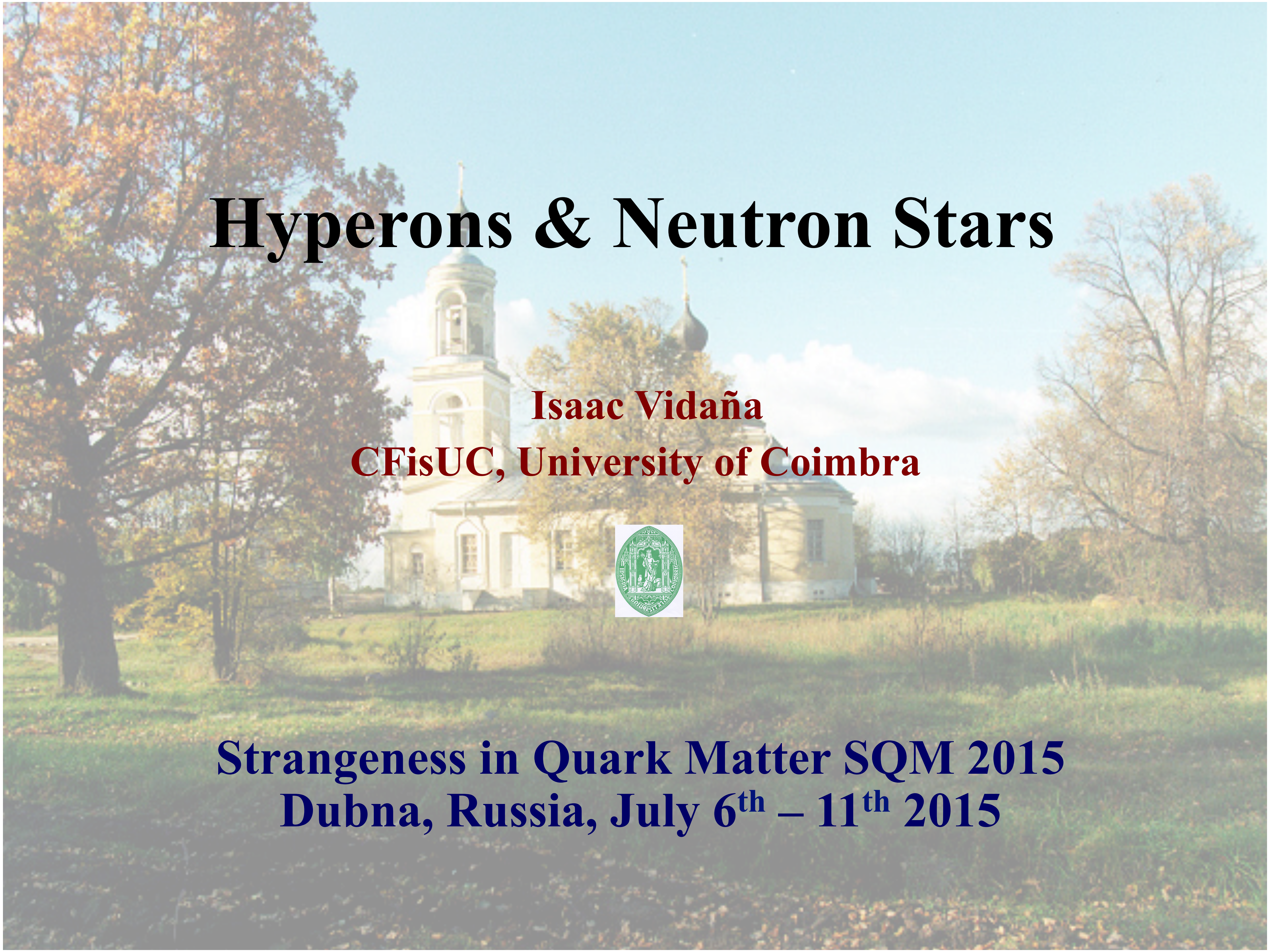


Hyperons & Neutron Stars

Isaac Vidaña
CFisUC, University of Coimbra

Strangeness in Quark Matter SQM 2015
Dubna, Russia, July 6th – 11th 2015

In this talk …

I will review the role of hyperons on :

- ❖ EoS & M_{max} of Neutron Stars
  (hyperon puzzle & possible solutions)
- ❖ Properties of Proto-Neutron Stars

If sometime is left …

- ❖ Neutron Star Cooling
- ❖ r-mode Instability of Neutron Stars

Neutron stars are different things for different people

- For astronomers are very little stars "visible" as radio pulsars or sources of X- and γ-rays.

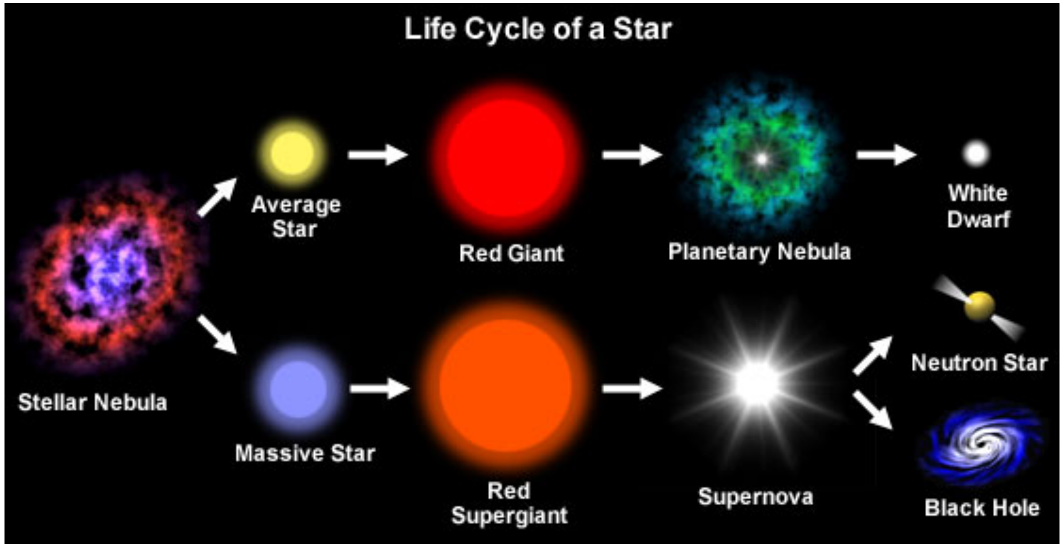
- For particle physicists are neutrino sources (when they born) and probably the only places in the universe where deconfined quark matter may be abundant.

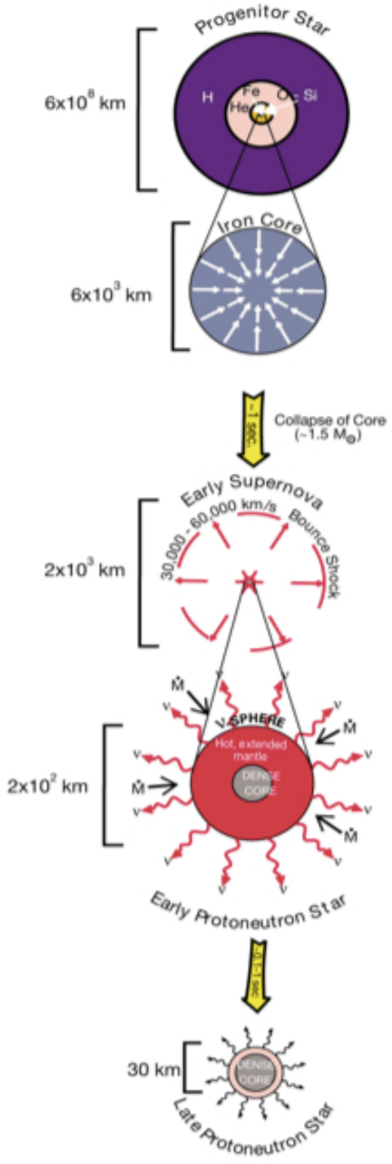
- For nuclear physicists are the biggest nuclei of the universe ($A \sim 10^{56}$-10^{57}, $R \sim 10$ km, $M \sim 1$-$2\ M_{\odot}$).

- For cosmologists are "almost" black holes

But everybody agrees that …

Neutron stars are a type of stellar compact remnant that can result from the gravitational collapse of a massive star ($8\ M_\odot < M < 25\ M_\odot$) during a Type II, Ib or Ic supernova event.





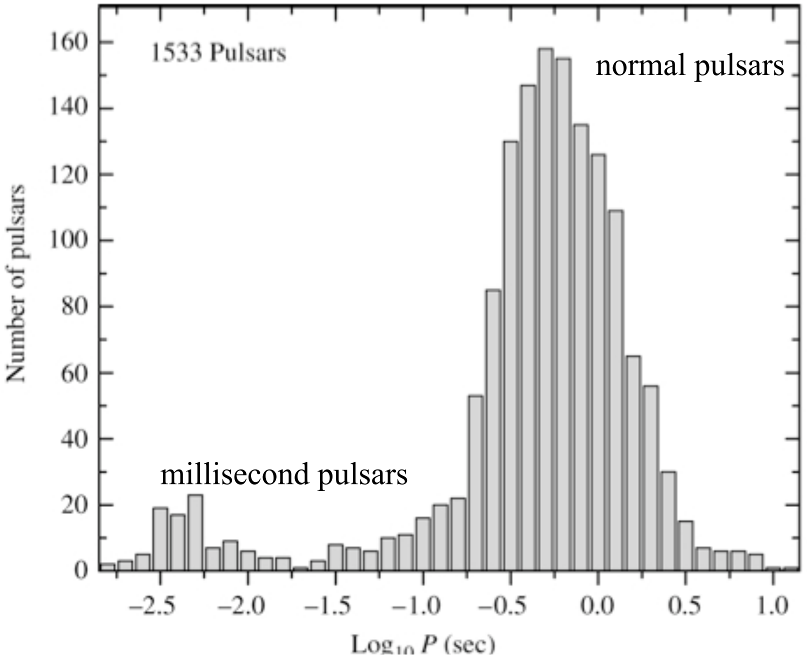
Some known facts about Neutron Stars

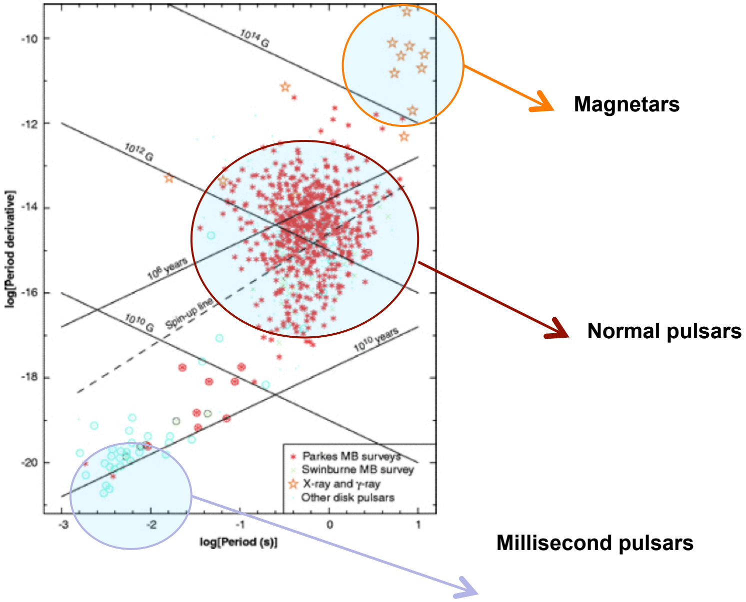
- Mass: $M \sim 1 - 2\, M_{\odot}$
- Radius: $R \sim\ 10 - 12$ km
- Density: $\rho \sim 10^{14} - 10^{15}$ g/cm^3
- Baryonic number: $N_b \sim 10^{57}$
- Most NS observed as pulsars

More than 2000 pulsars known
(~ 1900 radio, ~ 40 X-ray, ~ 60 γ-ray)

- Rotational period distribution
  ➔ two types of pulsars:

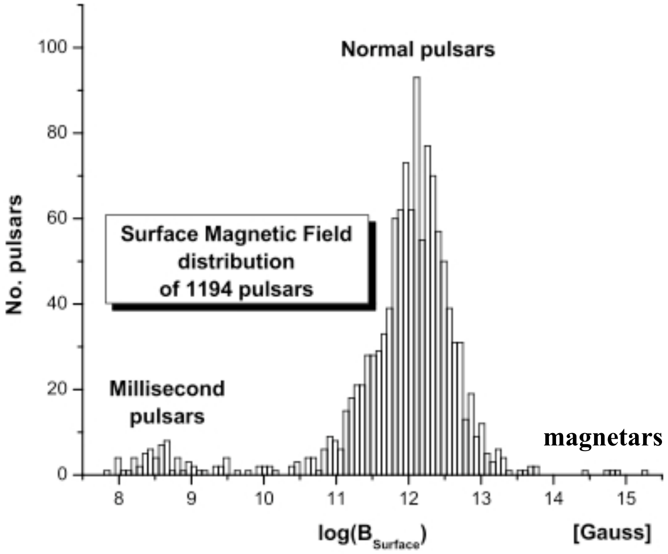
  - normal pulsars with P ~ s
  - millisecond pulsars with P ~ ms





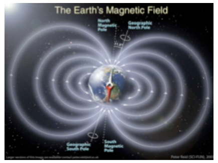
- Magnetic field

Type of Pulsar	Surface magnetic field
Millisecond	$10^8 – 10^9$ G
Normal	10^{12} G
Magnetar	$10^{14} – 10^{15}$ G



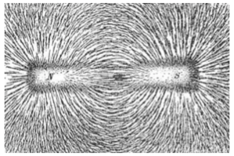
Extremely high compared to …

Earth



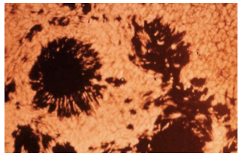
$0.3 - 0.5G$

Magnet



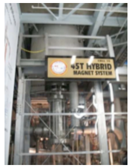
$10^3 - 10^4 G$

Sun spots



$10^5 G$

Largest continuous field in lab. (USA)



$4.5x10^5 G$

Largest magnetic pulse in lab. (Russia)

$2.8x10^7 G$

- Electric field: E ~ 10^{18} V/cm
- Temperature: T ~ $10^{6…11}$ K

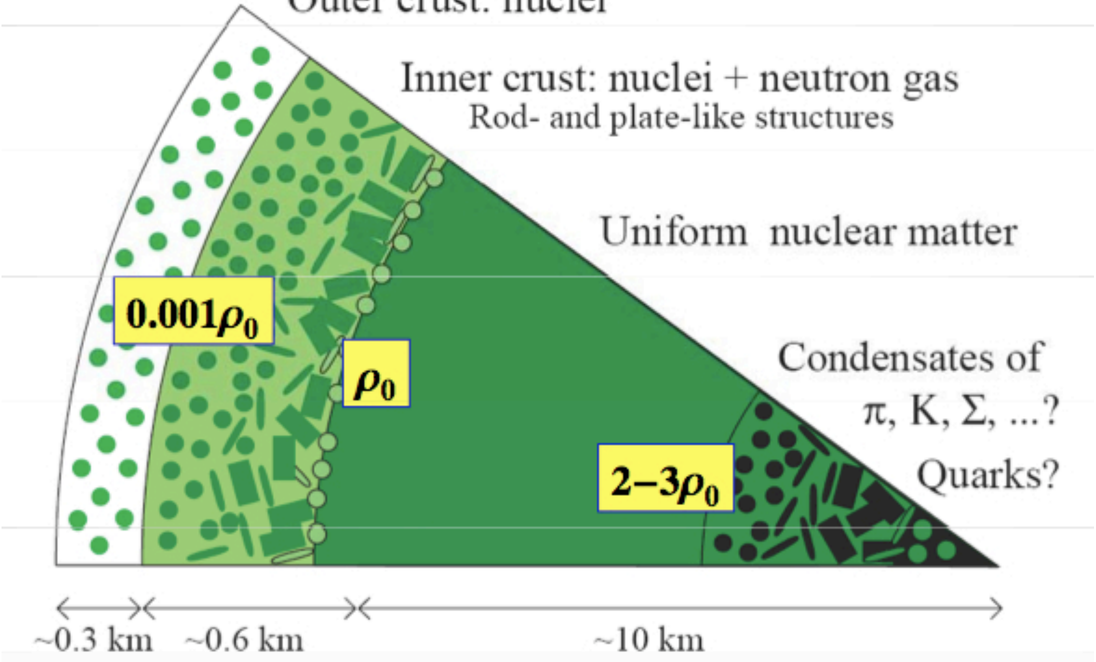
Anatomy of a Neutron Star

Equilibrium composition determined by

✓ Charge neutrality

$$\sum_i q_i \rho_i = 0$$

✓ Equilibrium with respect to weak interacting processes



$$b_1 \rightarrow b_2 + l + \bar{\nu}_l$$
$$b_2 + l \rightarrow b_1 + \nu_l$$

$$\longrightarrow \quad \mu_i = b_i \mu_n - q_i \left(\mu_e - \mu_{\nu_e} \right), \quad \mu_i = \frac{\partial \varepsilon}{\partial \rho_i}$$

Hyperons in Neutron Stars

Hyperons in NS considered by many authors since the pioneering work of Ambartsumyan & Saakyan (1960)

Phenomenological approaches

✧ Relativistic Mean Field Models: Glendenning 1985; Knorren et al. 1995; Shaffner-Bielich & Mishustin 1996, Bonano & Sedrakian 2012, …

✧ Non-realtivistic potential model: Balberg & Gal 1997

✧ Quark-meson coupling model: Pal et al. 1999, …

✧ Chiral Effective Lagrangians: Hanauske et al., 2000

✧ Density dependent hadron field models: Hofmann, Keil & Lenske 2001

Microscopic approaches

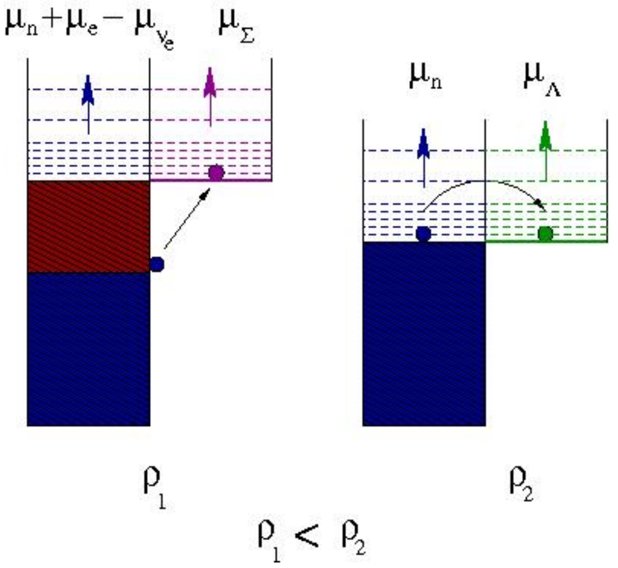
✧ Brueckner-Hartree-Fock theory: Baldo et al. 2000; I. V. et al. 2000, Schulze et al. 2006, I.V. et al. 2011, Burgio et al. 2011, Schulze & Rijken 2011

✧ DBHF: Sammarruca (2009), Katayama & Saito (2014)

✧ $V_{\mathrm{low}\ k}$: Djapo, Schaefer & Wambach, 2010

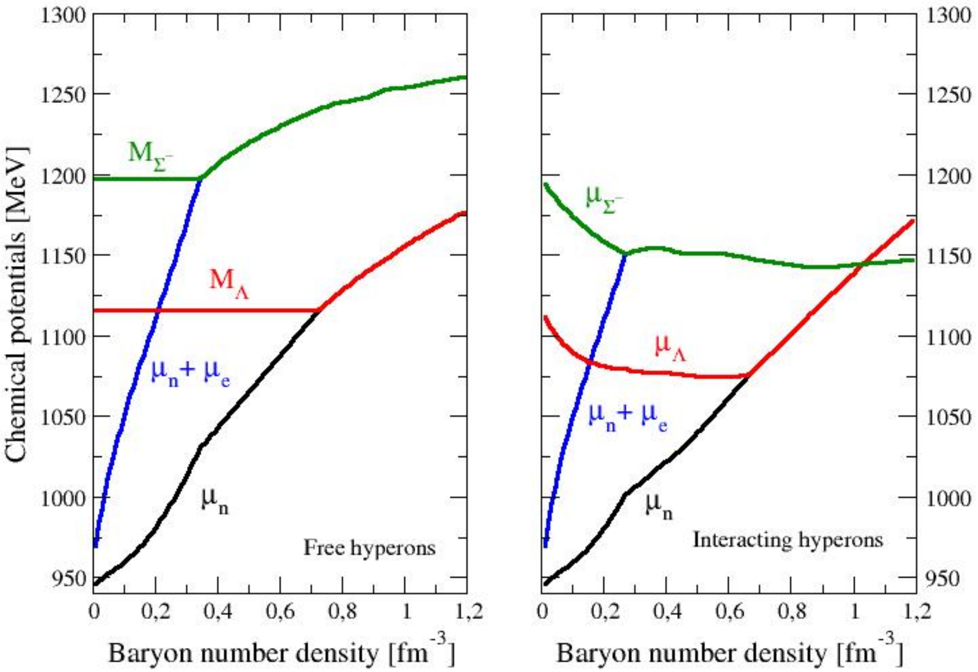
Sorry if I missed somebody

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make the conversion of N into Y energetically favorable.



$$\mu_{\Sigma^-} = \mu_n + \mu_{e^-} - \mu_{\nu_{e^-}}$$

$$\mu_\Lambda = \mu_n$$



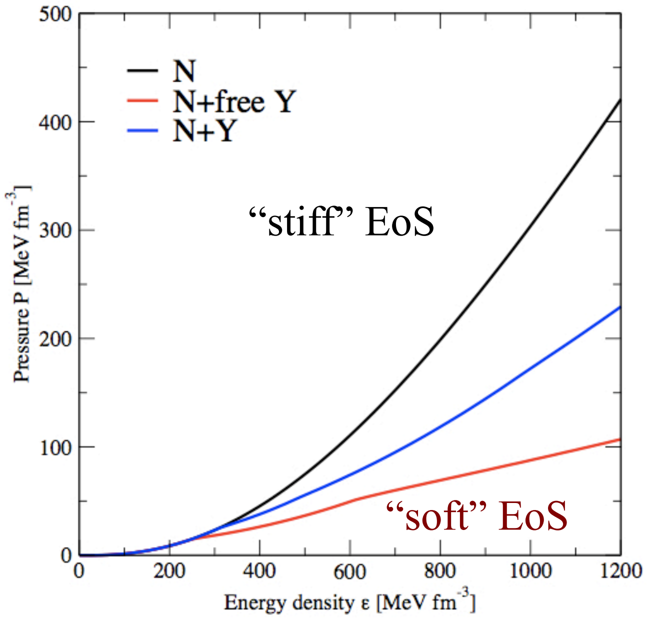
$$n + n \rightarrow n + \Lambda$$

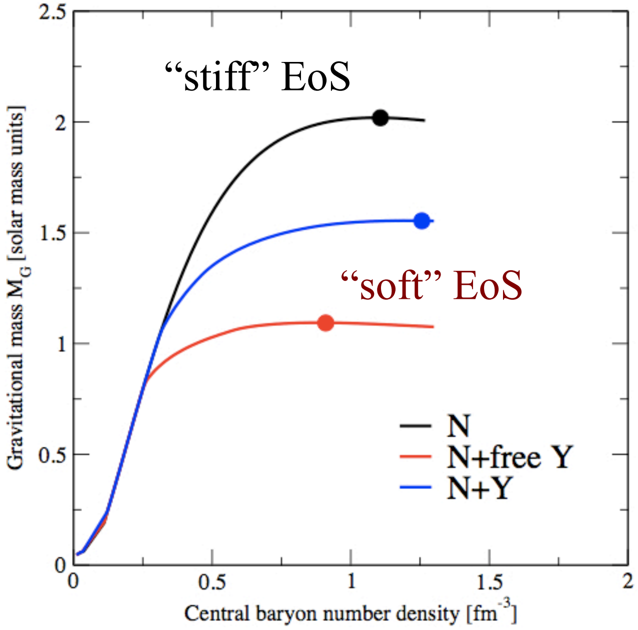
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

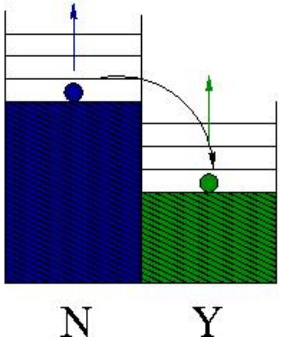
$$n + n \rightarrow p + \Sigma^-$$

$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

Effect of Hyperons in the EoS and Mass of Neutron Stars



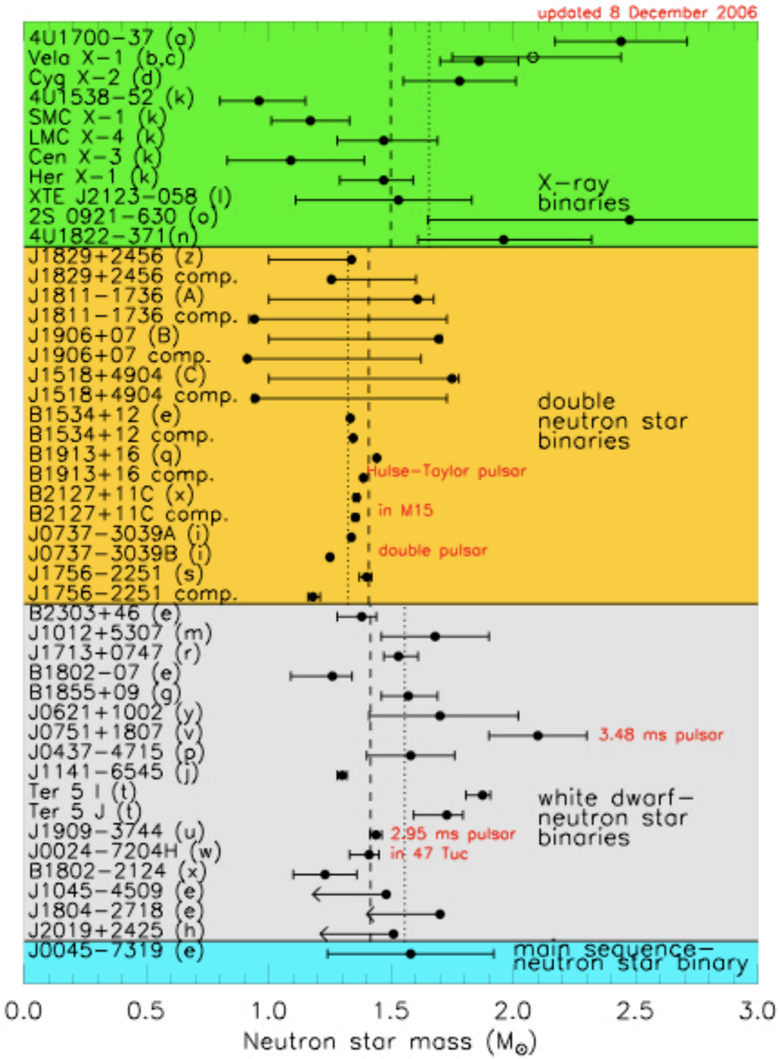




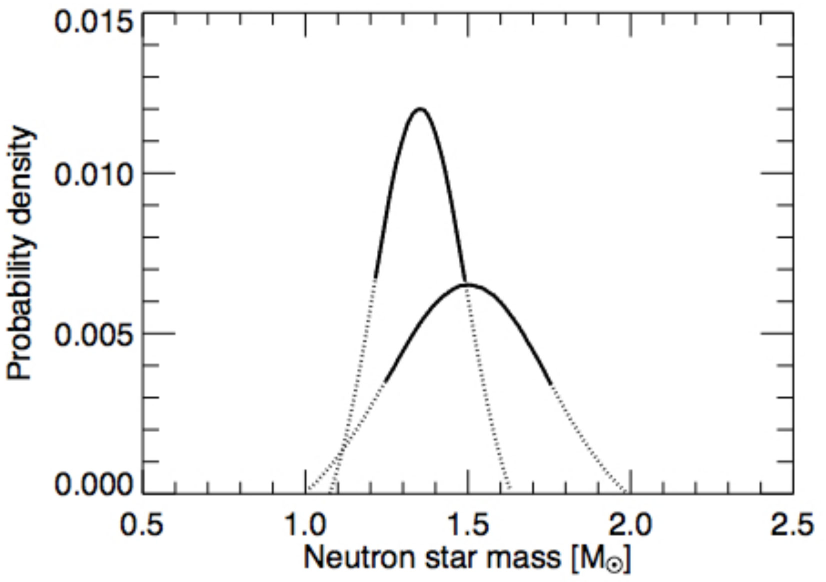
Relieve of Fermi pressure due to the appearance of hyperons ➔

EoS softer ➔ reduction of the mass

Measured Neutron Star Masses (up to ~ 2006-2008)



(Lattimer & Prakash 2007)

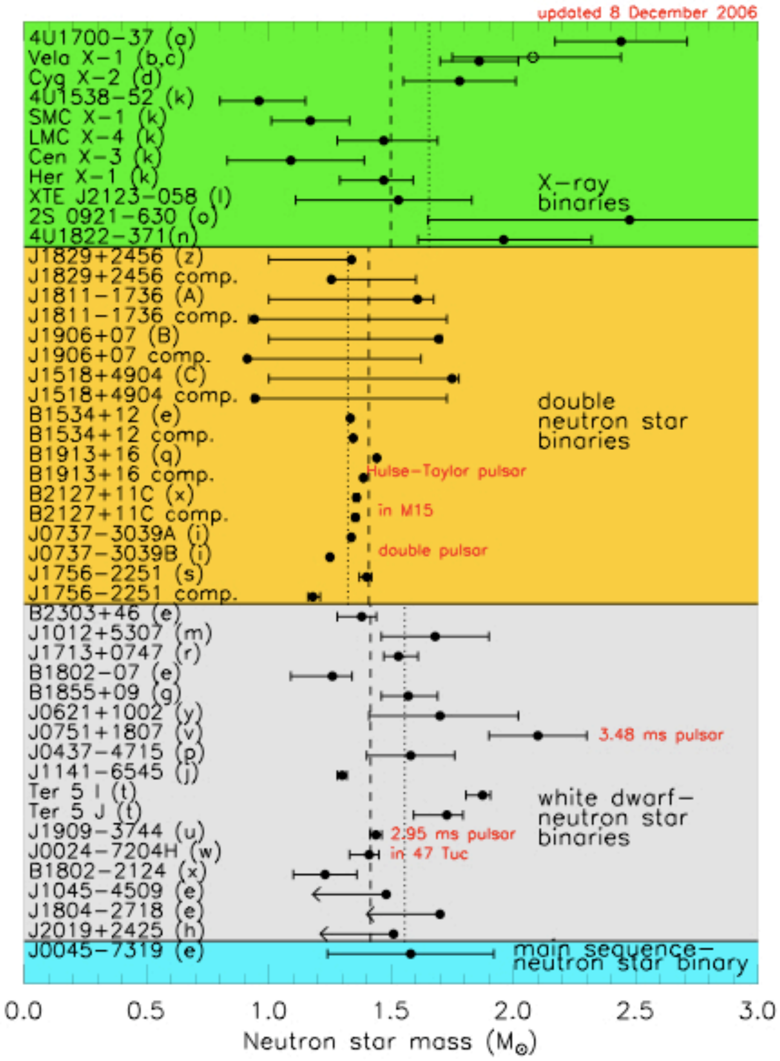


up to ~ 2006-2008 any valid
EoS should predict

$$M_{\max}\left[EoS\right] > 1.4 - 1.5 M_{\odot}$$

Hyperons in NS

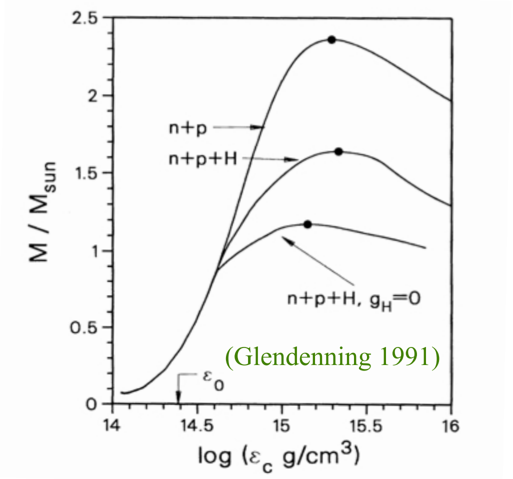
(up to ~ 2006-2008)



(Lattimer & Prakash 2007)

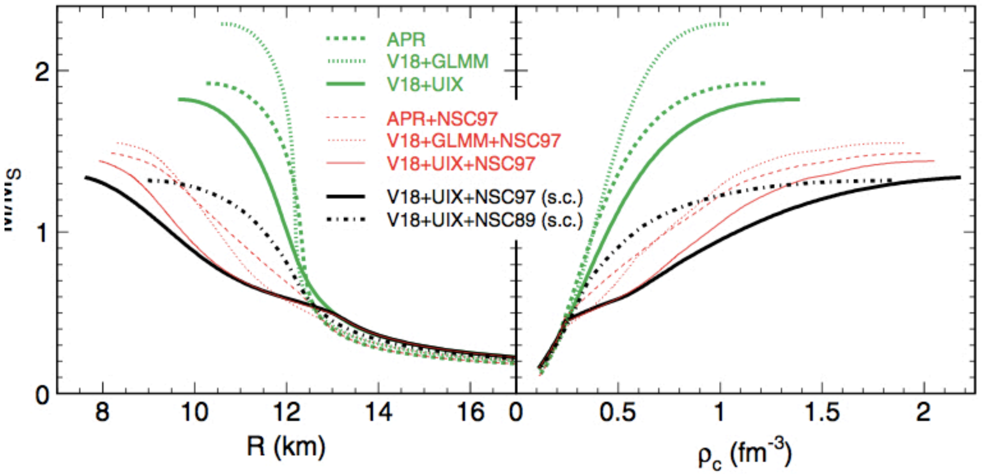
Phenomenological:

M_{max} compatible with 1.4-1.5 $M_\odot$



(Glendenning 1991)

Microscopic : M_{max} < 1.4-1.5 $M_\odot$



(Schulze, Polls, Ramos & IV 2006)

Recent measurements of high masses → life of hyperons more difficult

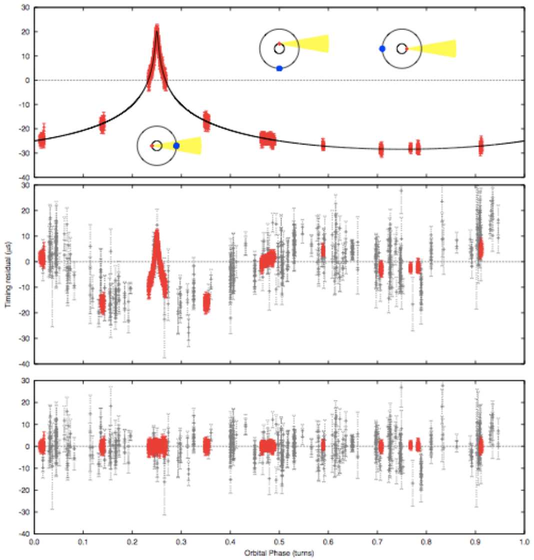
- **PSR J164-2230** (Demorest et al. 2010)

✓ binary system (P=8.68 d)

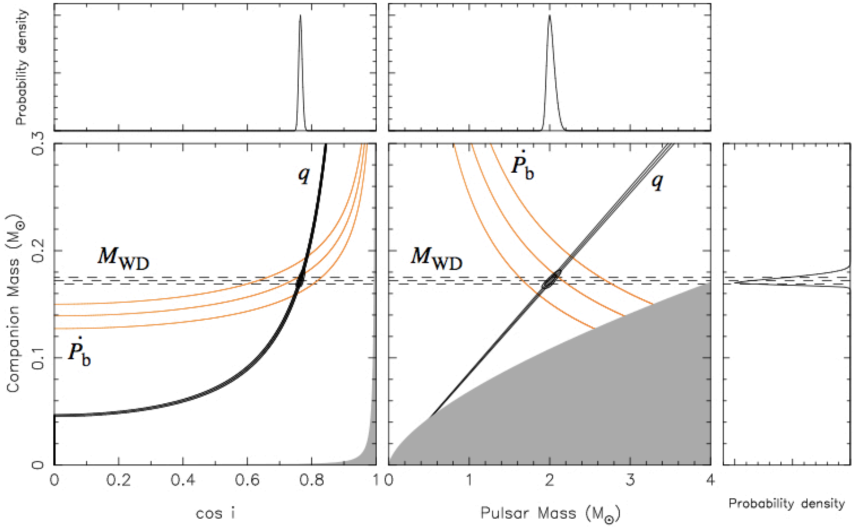
✓ eccentricity (e=1.3 x 10^{-6})

✓ companion mass: $\sim 0.5 M_\odot$

✓ pulsar mass: $M = 1.97 \pm 0.04 M_\odot$



- **PSR J0348+0432** (Antoniadis et al. 2013)



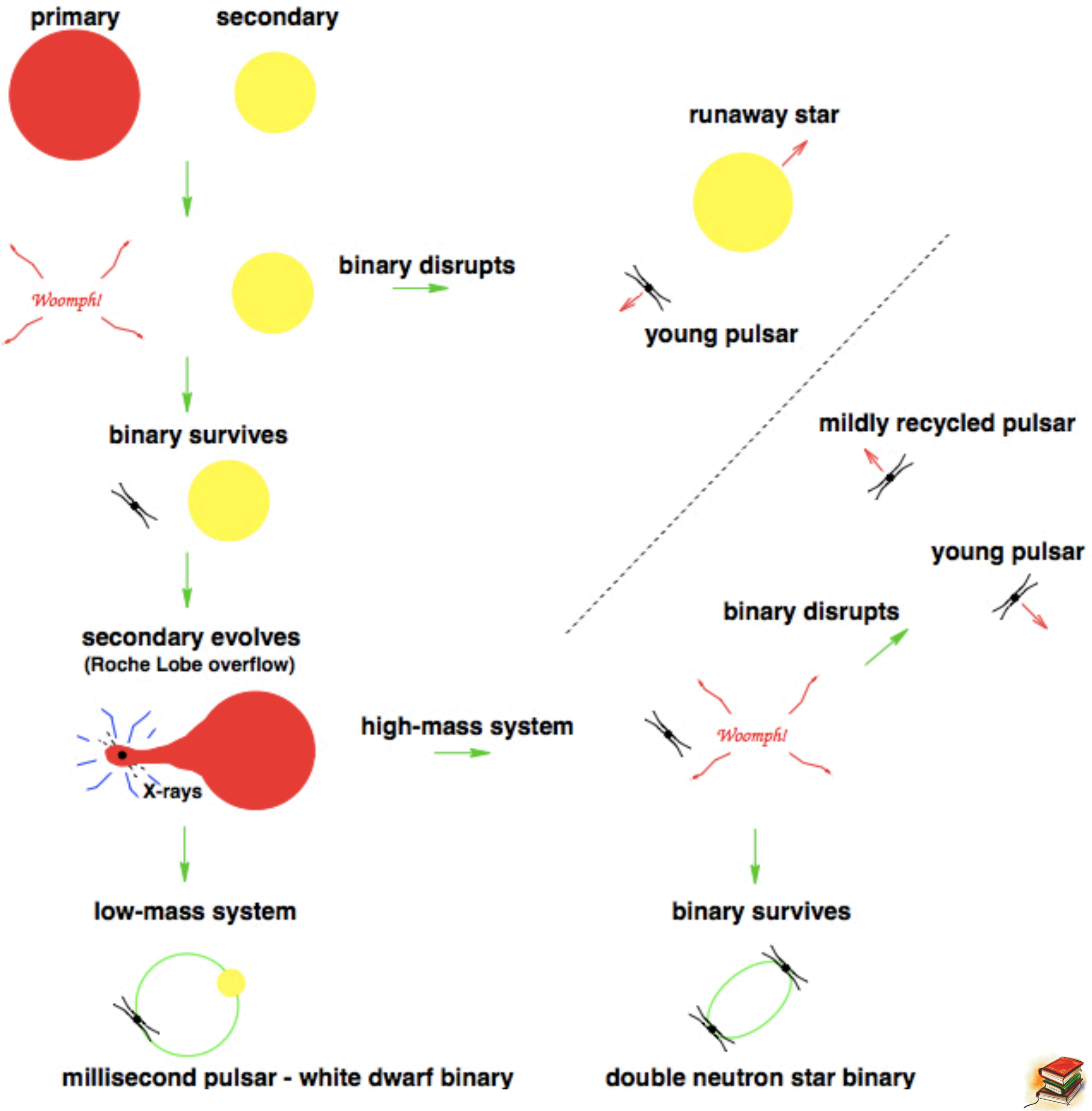
✓ binary system (P=2.46 h)

✓ very low eccentricity

✓ companion mass: $0.172 \pm 0.003 M_\odot$

✓ pulsar mass: $M = 2.01 \pm 0.04 M_\odot$

Formation of Binary Systems



primary

secondary

runaway star

binary disrupts

young pulsar

binary survives

mildly recycled pulsar

young pulsar

binary disrupts

secondary evolves
(Roche Lobe overflow)

high-mass system

low-mass system

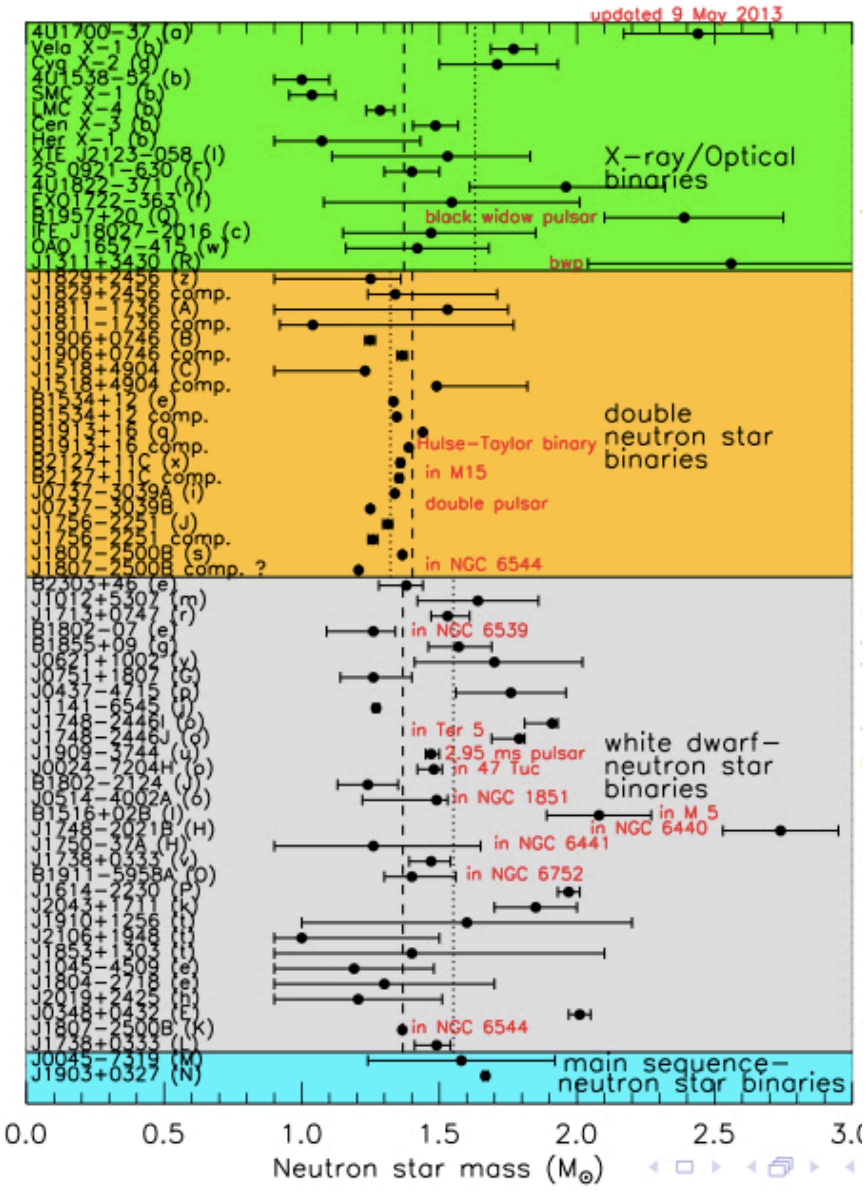
binary survives

millisecond pulsar - white dwarf binary

double neutron star binary

Figure by P.C.C. Freire

Measured Neutron Star Masses (2015)



updated from Lattimer 2013

Observation of ~ 2 $M_\odot$ neutron stars

↓

Dense matter EoS stiff enough is required such that

$$M_{\max}\left[EoS\right] > 2M_\odot$$

Can hyperons still be present in the interior of neutron stars in view of this constraint ?

The Hyperon Puzzle

"Hyperons → "soft (or too soft) EoS" not compatible (mainly in microscopic approaches) with measured (high) masses. However, the presence of hyperons in the NS interior seems to be unavoidable."

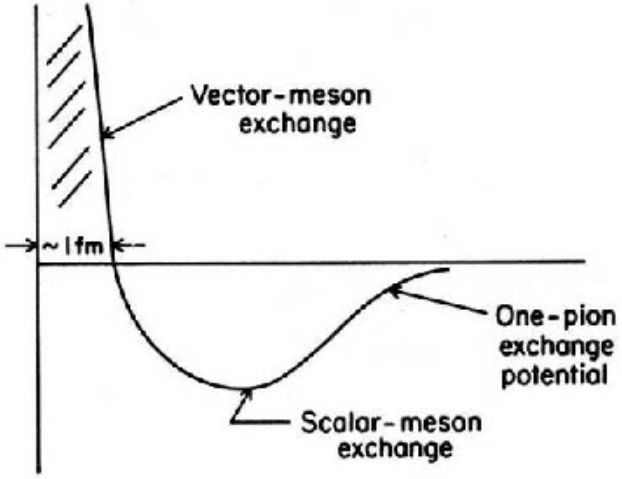
- ✓ can YN & YY interactions still solve it ?
- ✓ or perhaps hyperonic three-body forces ?
- ✓ what about quark matter ?

Solution I: YY vector meson repulsion

(explored in the context of RMF models)

General Feature:

Exchange of scalar mesons generates attraction (softening), but the exchange of vector mesons generates repulsion (stiffening)



Add vector mesons with hidden strangeness (ϕ) coupled to hyperons yielding a strong repulsive contribution at high densities

Dexhamer & Schramm (2008), Bednarek et al, (2012), Weissenborn et al., (2012)
Oertel et al. (2014), Maslov et al. (2015)

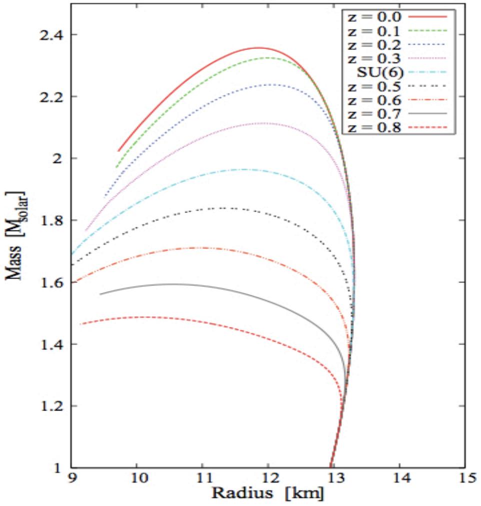
Weissenborn et al. (2012)

- ✓ σ^2, σ^3, σ^4 terms
- ✓ ρ^2, ω^2, ω^4 terms
- ✓ “hidden strangeness” mesons: σ^*, ϕ

  (σ^{*2}, ϕ^2)
- ✓ g_{YV} couplings: from SU(6) to SU(3)

  vary $z=g_8/g_1$ & $\alpha=F/(F+D)$
- ✓ g_{YS} couplings adjusted by fitting $U_B^{(N)}$

  ($U_\Lambda^{(N)}=-30$, $U_\Sigma^{(N)}=+30$, $U_\Xi^{(N)}=-28$ MeV)

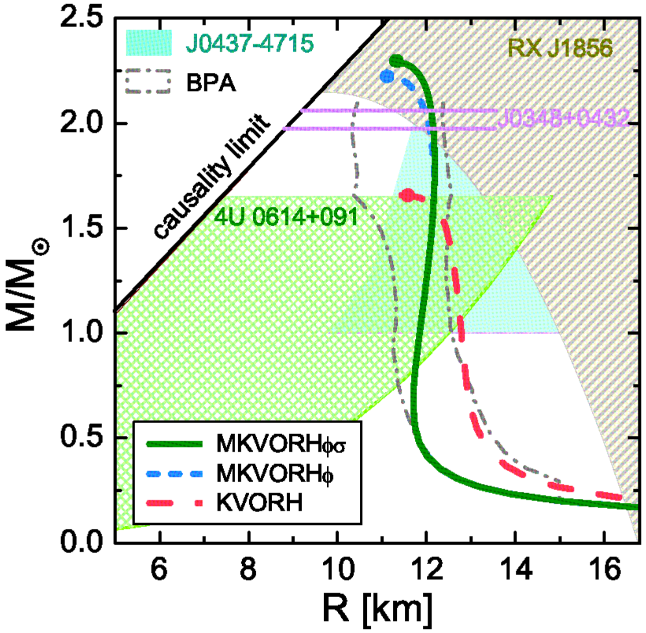


M_{max} compatible with $2M_\odot$

Maslov et al. (2015)

(Kolomeitsev’s talk on session “Strangeness in Astrophysics” on Tuesday July 6th)

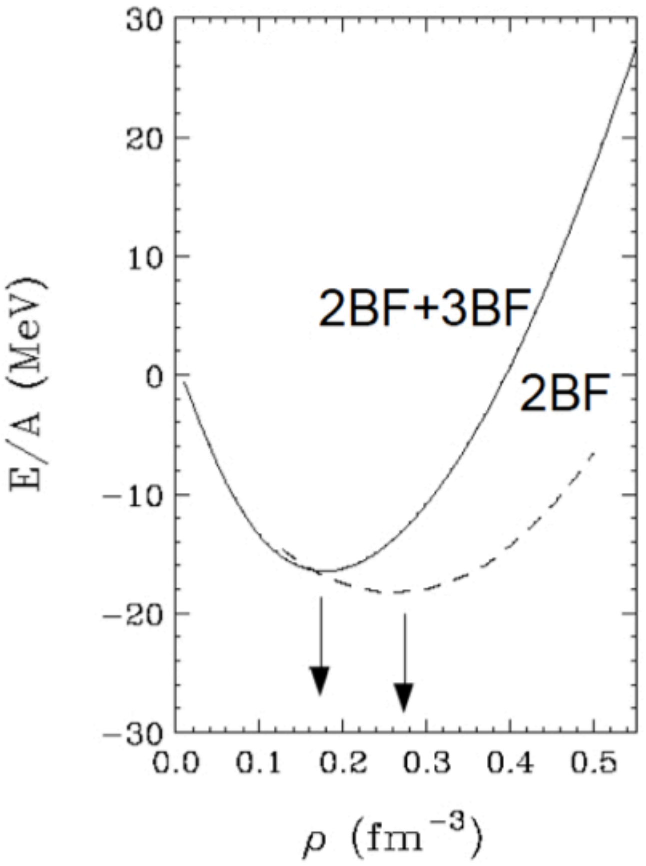
- ✓ RMF with scaled hadron masses (universal) & coupling constants (not universal)
- ✓ Model flexible enough to satisfy constraints from HIC & astrophysical data
- ✓ Hyperon puzzle <u>partially solved if a reduction of ϕ meson mass is included</u>



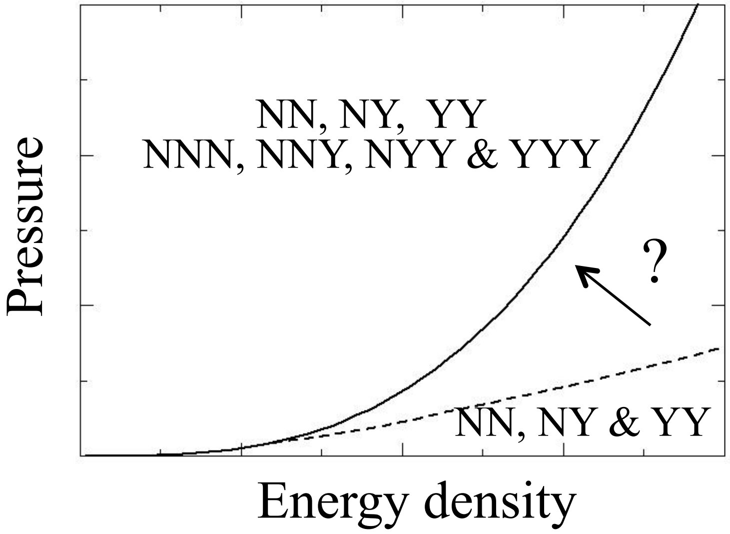
Solution II: can Hyperonic TBF solve this puzzle ?

Natural solution based on: Importance of NNN force in Nuclear Physics
(Considered by several authors: Chalk, Gal, Usmani, Bodmer, Takatsuka, Loiseau, Nogami, Bahaduri, IV)

NNN Force



NNY, NYY & YYY Forces

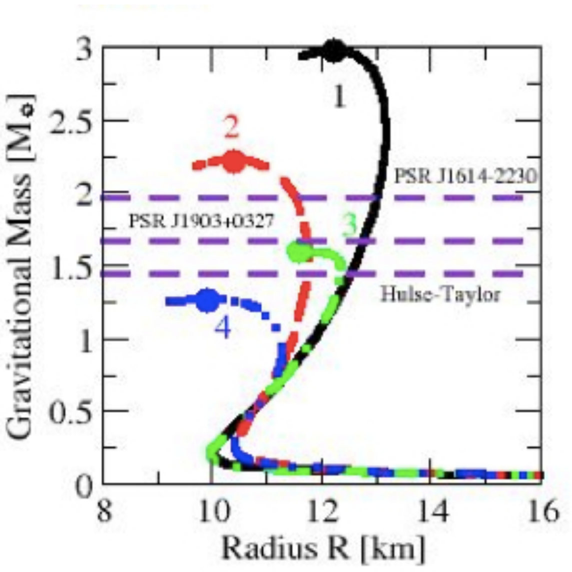


Can hyperonic TBF provide enough repulsion at high densities to reach $2M_\odot$?

The results are contradictory

I. V. et al. (2011)

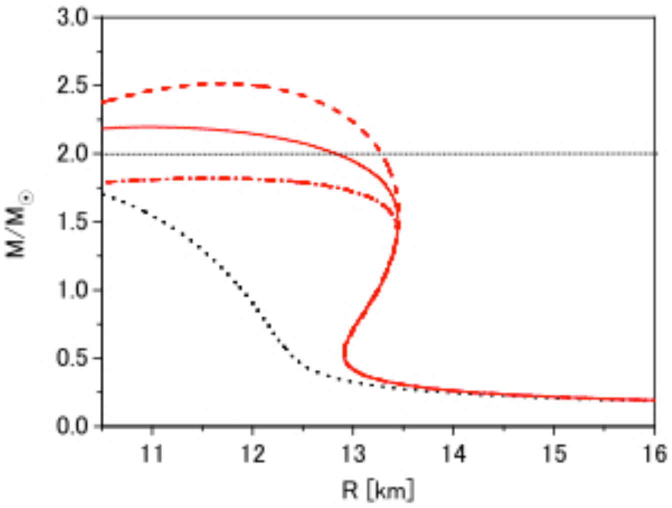
BHF with NN+YN+phenomenological YTBF. Different strength of YTBF including the case of universal TBF



$$1.27 < M_{\max} < 1.6 M_\odot$$

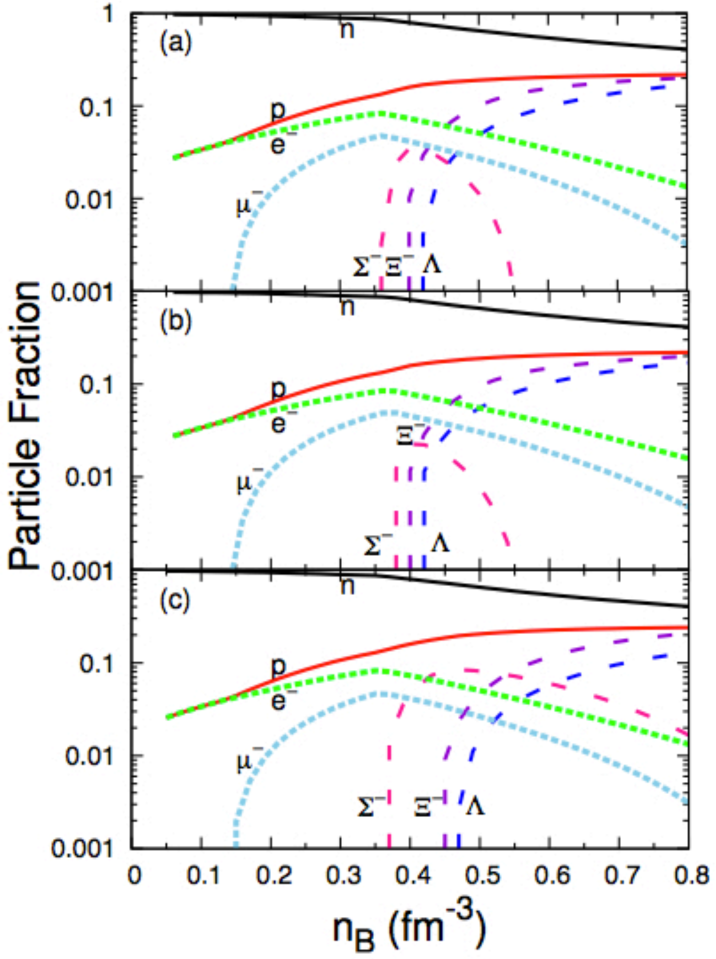
Yamamoto et al. (2015)

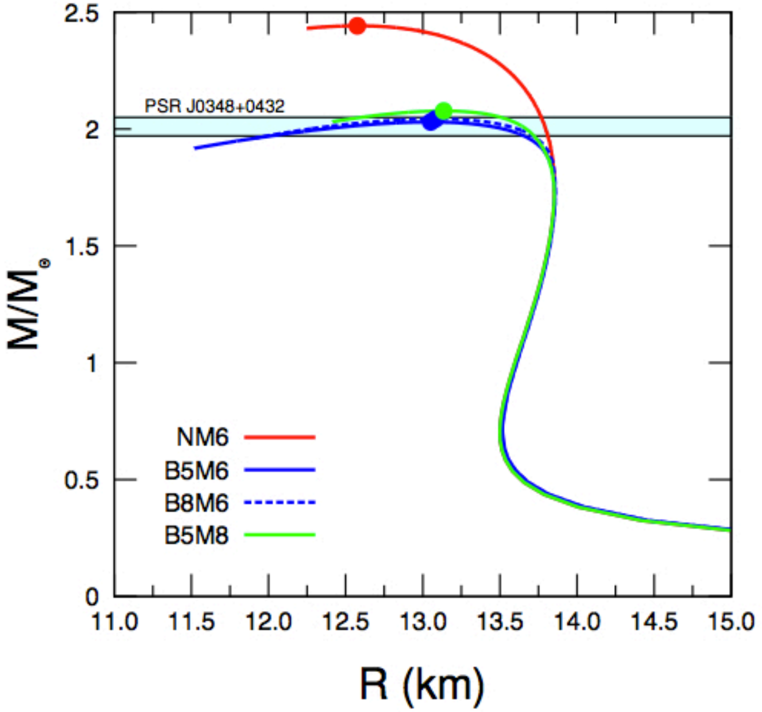
BHF with NN+YN+universal repulsive TBF (multipomeron exchange mecanism)



$$M_{\max} > 2M_\odot$$

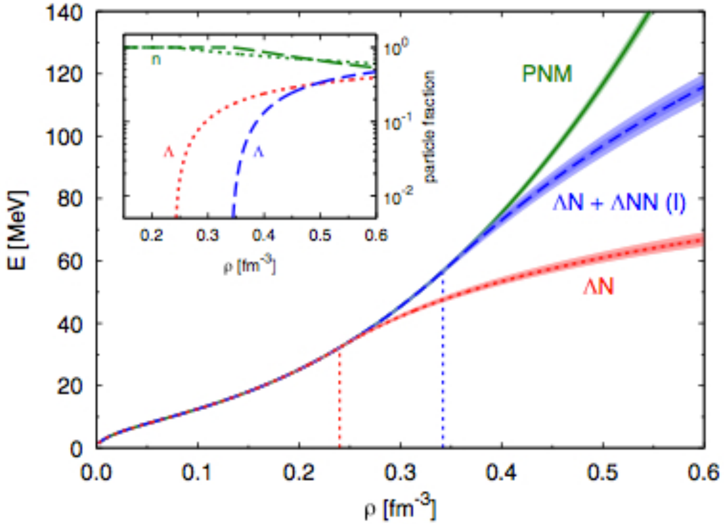
It should be mentioned also the recent DBHF calculation of hyperonic matter by Katayama & Saito (2014)

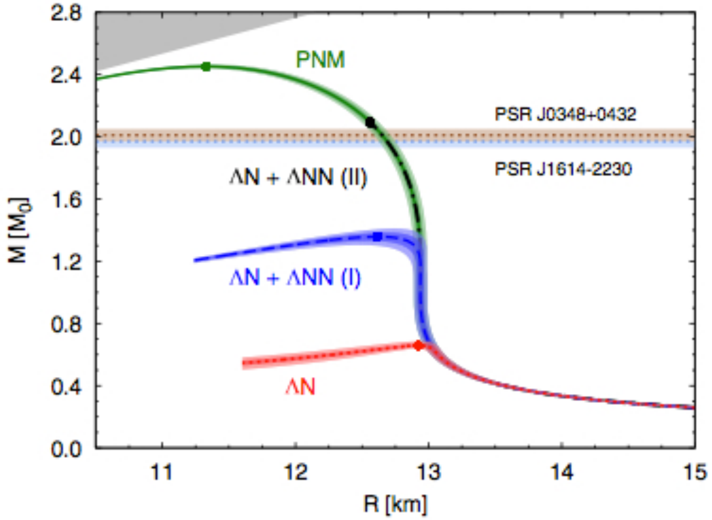




- DBHF includes some TBF effects in a natural way
- M_{max} compatible with $2M_\odot$
- But the construction of YN is a bit obscure in this work

and the recent Quantum Monte Carlo calculation by Lonardoni et al. (2015)





- First Quantum Monte Carlo calculation on neutron+Λ matter

- Strong dependence of Λ onset on Λnn force

- Some of the parametrizations of the Λnn force give maximum masses compatible with $2M_\odot$ but the onset of Λ is above the maximum density considered (~0.56 fm^{-3}). So in fact, no Λs are present in NS interior

Solution III: Quark Matter Core

General Feature:

Some authors have suggested that the hyperon core in neutron stars could be replaced by a cores of uds quark mater. Massive neutron stars could actually be hybrid stars with a stiff quark matter core

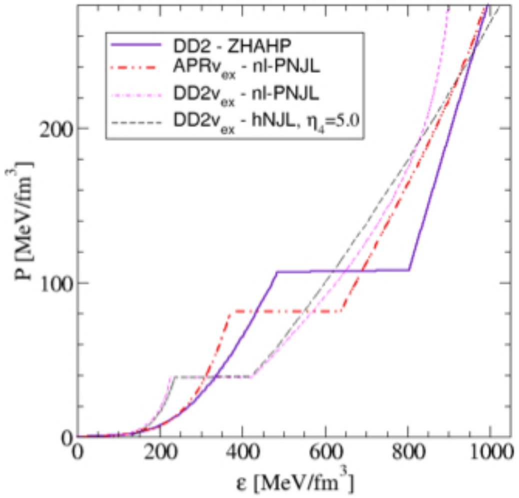
To yield $M_{\max} > 2M_{\odot}$ Quark Matter should have:

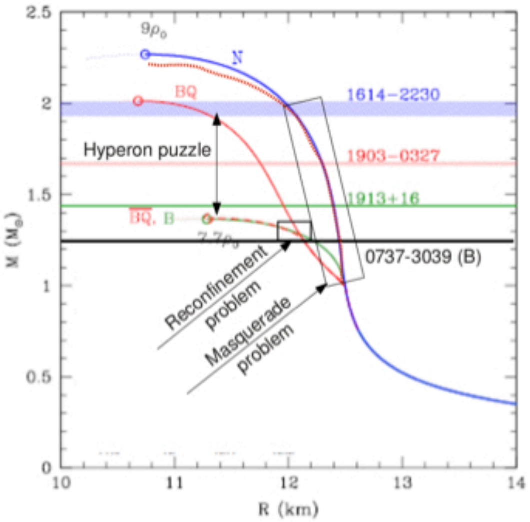
- significant overall quark repulsion → stiff EoS
- strong attraction in a channel → strong color superconductivity

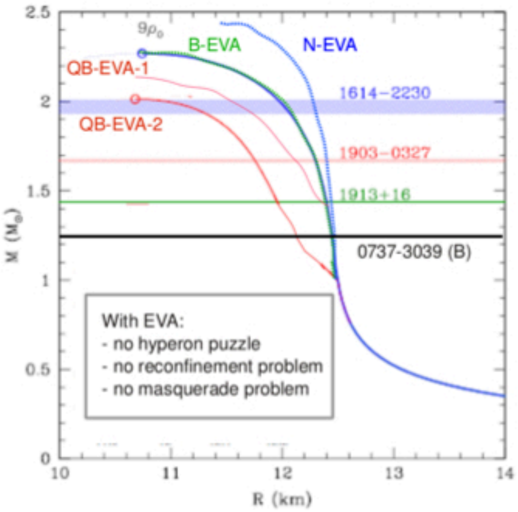
Ozel et al., (2010), Weissenborn et al., (2011), Klaehn et al., (2011), Bonano & Sedrakian (2012), Lastowiecki et al., (2012), Zdunik & Haensel (2012)

A recent work by Blaschke & Alvarez-Castillo (2015)

(Alvarez-Castillo's talk on session "Strangeness in Astrophysics" on Tuesday July 6th)







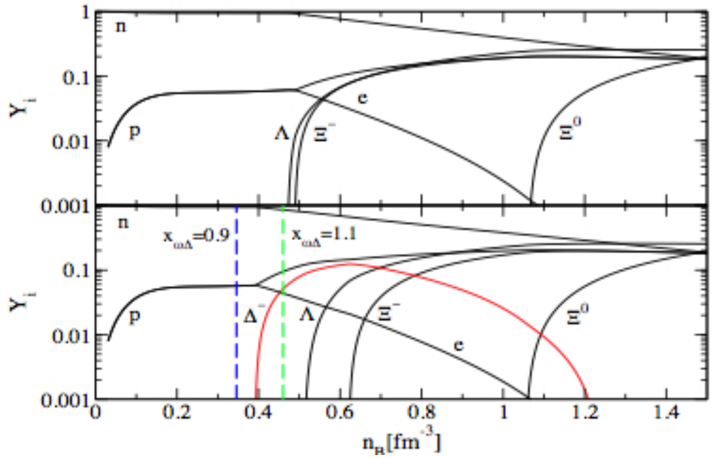
Compositeness of baryons (by excluded volume and/or quark Pauli blocking) on the hadronic side + confinement and stiffening effects on the quark matter:

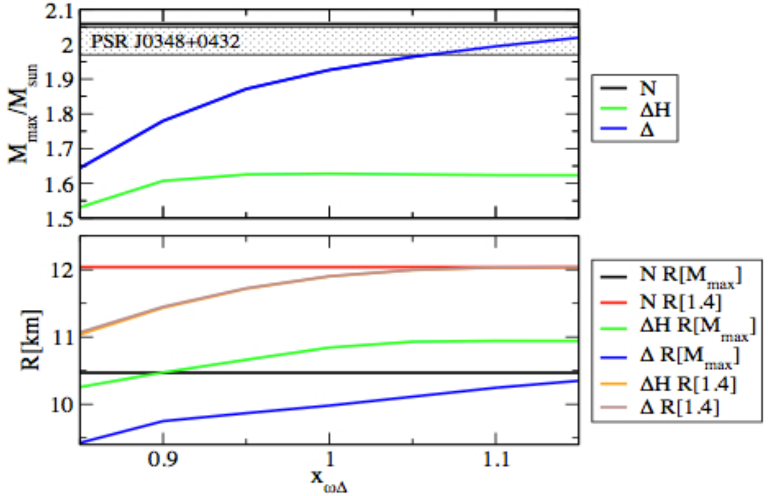
→

Earlier phase transition to QM with sufficient stiffening at high densities to solve: hyperon puzzle, masquerade problem & reconfinement puzzle

Is there also a Δ isobar puzzle ?

The recent work by Drago et al. (2014) calculation have studied the role of the Δ isobar in neutron star matter



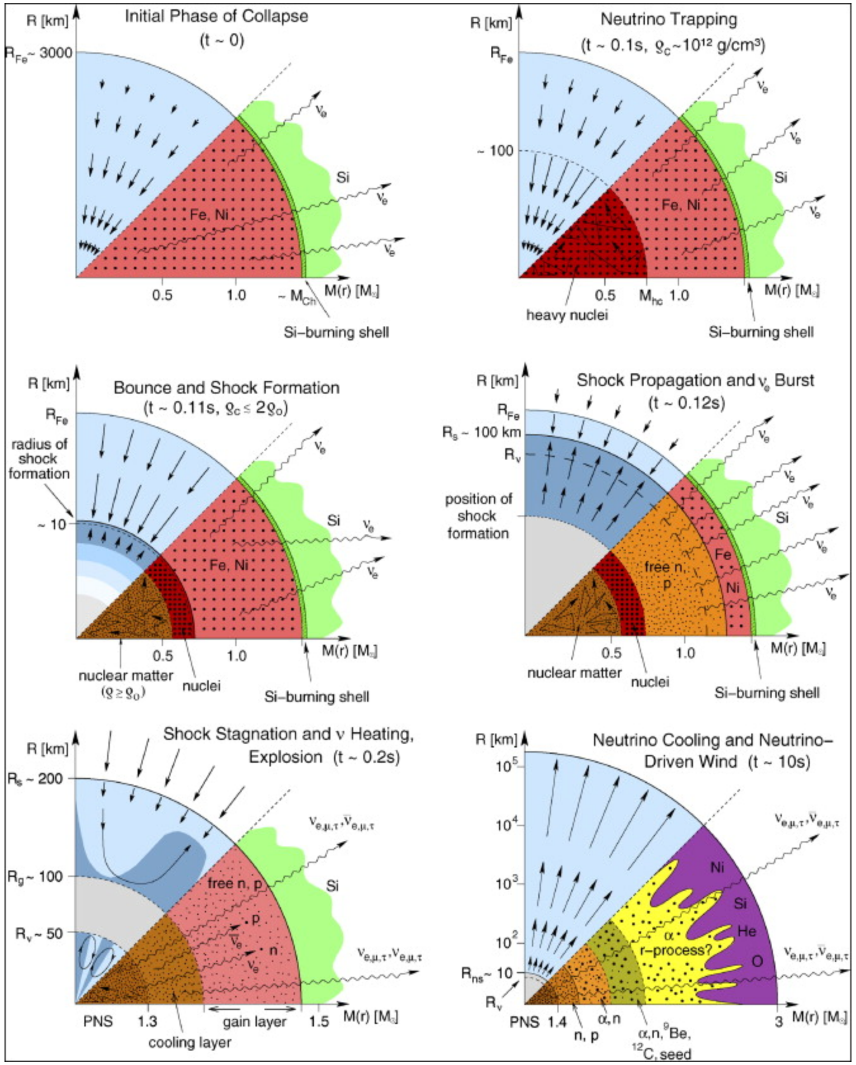


- Constraints from L indicate an early appearance of Δ isobars in neutron stars matter at ~ 2-3 ρ_0 (same range as hyperons)
- Appearance of Δ isobars modify the composition & structure of hadronic stars
- M_{max} is dramatically afected by the presence of Δ isobars

If Δ potential is close to that indicated by π−, e-nucleus or photoabsortion nuclear reactions then EoS is too soft ⟶ Δ puzzle similar to the hyperon one

Hyperon Stars at Birth

Proto-Neutron Stars



(Janka, Langanke, Marek, Martinez-Pinedo & Muller 2006)

New effects on PNS matter:

- Thermal effects

$$T \cong 30-40 \quad MeV$$

$$S/A \cong 1-2$$

- Neutrino trapping

$$\mu_\nu \neq 0$$

$$Y_e = \frac{\rho_e + \rho_{\nu_e}}{\rho_B} \approx 0.4$$

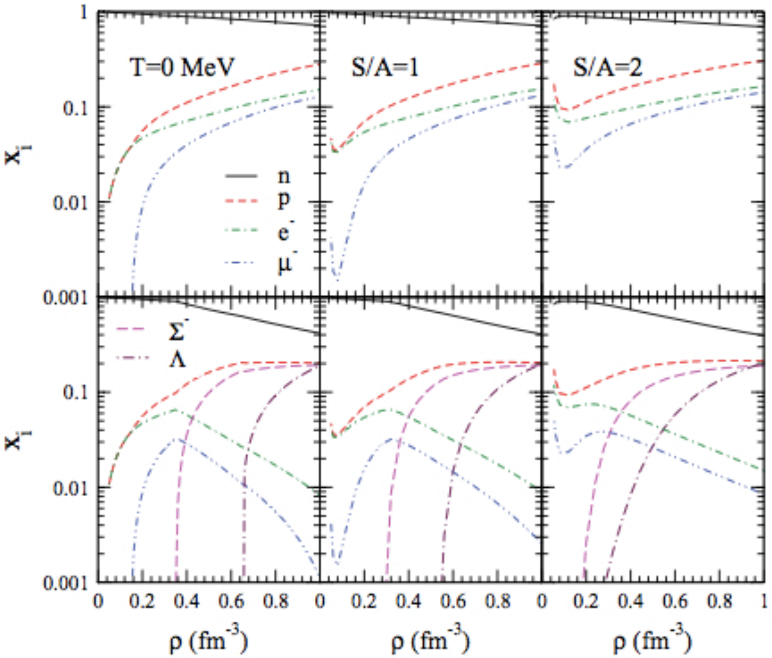
$$Y_\mu = \frac{\rho_\mu + \rho_{\nu_\mu}}{\rho_B} \approx 0$$

Proto-Neutron Stars: Composition

- Neutrino free

$\mu_\nu = 0$

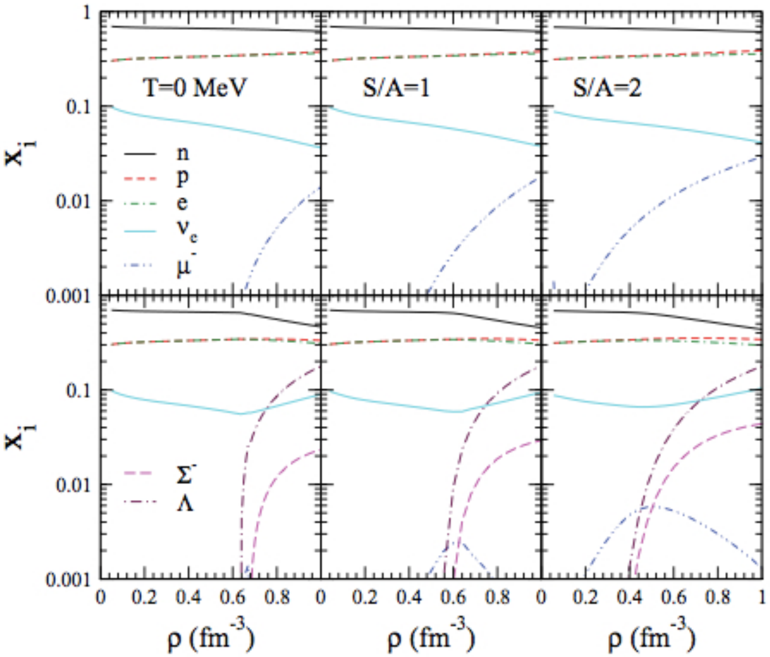
(Burgio & Schulze 2011)



- Neutrino trapped

$\mu_\nu \neq 0$

(Burgio & Schulze 2011)

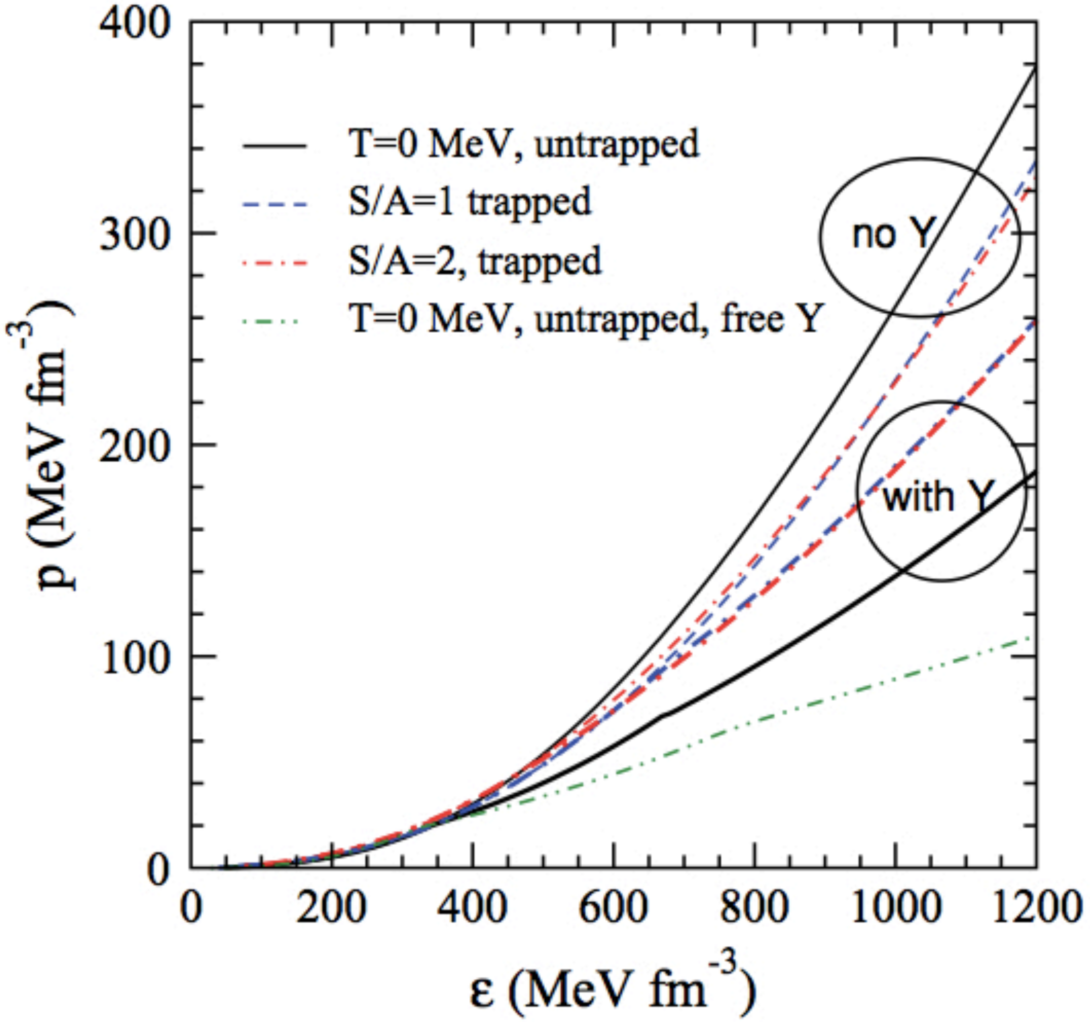


Neutrino trapped

- ✓ Large proton fraction
- ✓ Small number of muons
- ✓ Onset of $\Sigma^-(\Lambda)$ shifted to higher (lower) density
- ✓ Hyperon fraction lower in ν-trapped matter

Proto-Neutron Stars: EoS

(Burgio & Schulze 2011)



- Nucleonic matter

✧ ν-trapping + temperature
⟶ <u>softer EoS</u>

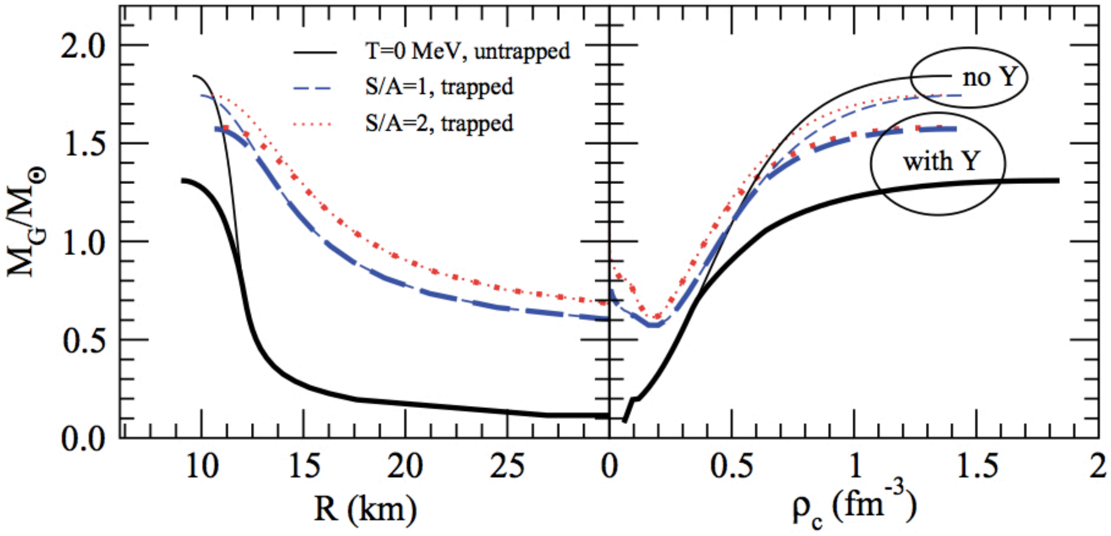
- Hyperonic matter

✧ ν-trapping + temperature
⟶ <u>stiffer EoS</u>

✧ More hyperon softening
in ν-untrapped matter
(larger hyperon fraction)

Proto-Neutron Stars: Structure

(Burgio & Schulze 2011)



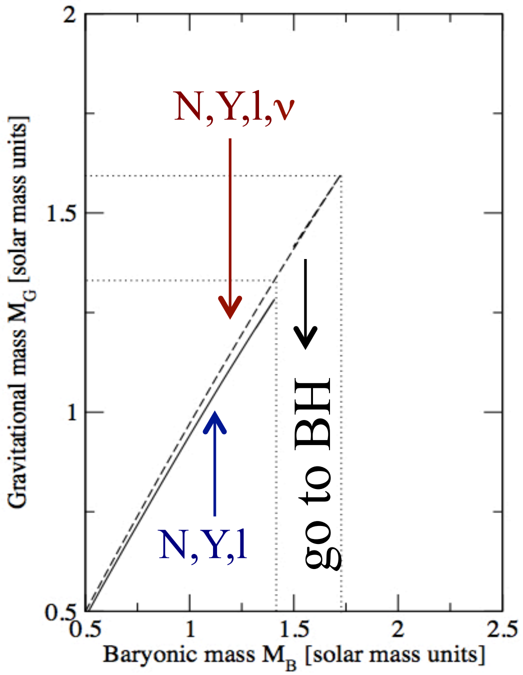
- Nucleonic matter

  ν-trapping + T:
  reduction of M_{max}

- Hyperonic matter

  ν-trapping + T:
  increase of M_{max} → delayed formation of a low mass BH

(IV et al. 2003)

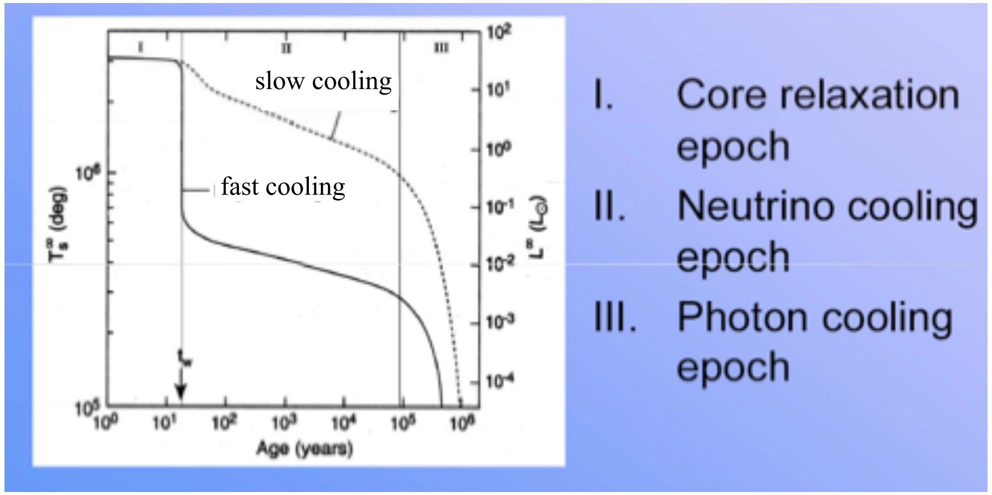


Hyperons & Neutron Star Cooling

Neutron Star Cooling in a Nutshell

Two cooling regimes

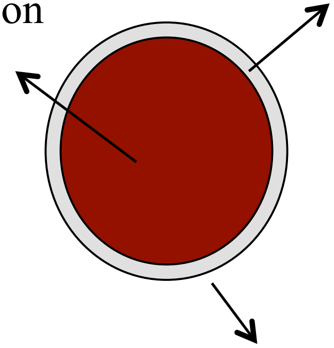
Slow	Fast
Low NS mass	High NS mass



I. Core relaxation epoch

II. Neutrino cooling epoch

III. Photon cooling epoch



Core cools by neutrino emission

Crust cools by conduction

Surface photon emission dominates at t > 10^6 yrs

$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\gamma - L_\nu + H$$

- ✓ C_v: specific heat
- ✓ L_γ: photon luminosity
- ✓ L_ν: neutrino luminosity
- ✓ H: “heating”

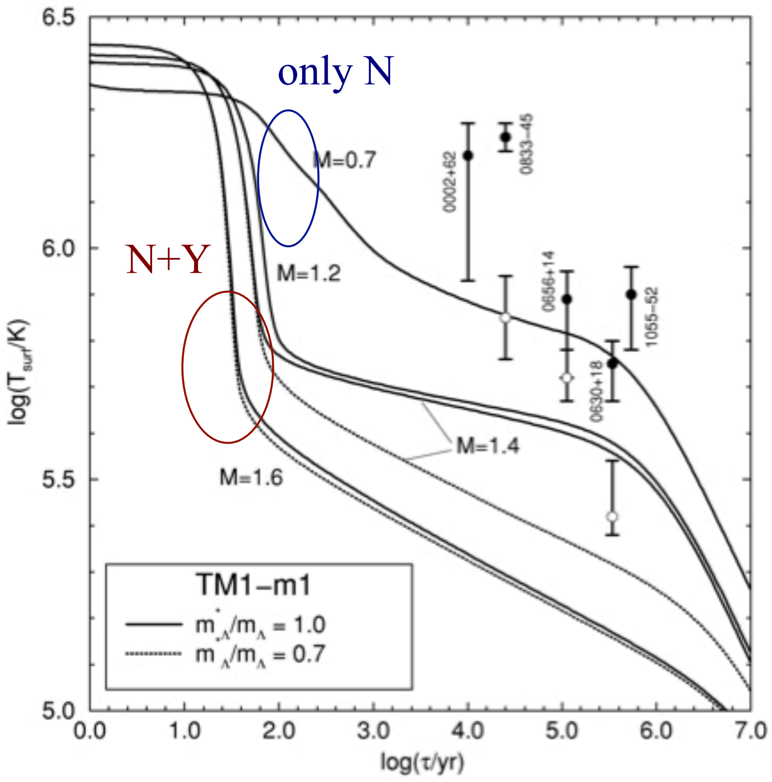
Hyperonic DURCA processes possible as soon as hyperons appear (nucleonic DURCA requires $x_p > 11\text{-}15\ \%$)

→ **Additional Fast Cooling Processes**

Process	R
$\Lambda \rightarrow p + l + \bar{\nu}_l$	0.0394
$\Sigma^- \rightarrow n + l + \bar{\nu}_l$	0.0125
$\Sigma^- \rightarrow \Lambda + l + \bar{\nu}_l$	0.2055
$\Sigma^- \rightarrow \Sigma^0 + l + \bar{\nu}_l$	0.6052
$\Xi^- \rightarrow \Lambda + l + \bar{\nu}_l$	0.0175
$\Xi^- \rightarrow \Sigma^0 + l + \bar{\nu}_l$	0.0282
$\Xi^0 \rightarrow \Sigma^+ + l + \bar{\nu}_l$	0.0564
$\Xi^- \rightarrow \Xi^0 + l + \bar{\nu}_l$	0.2218

+ partner reactions generating neutrinos,
Hyperonic MURCA, …

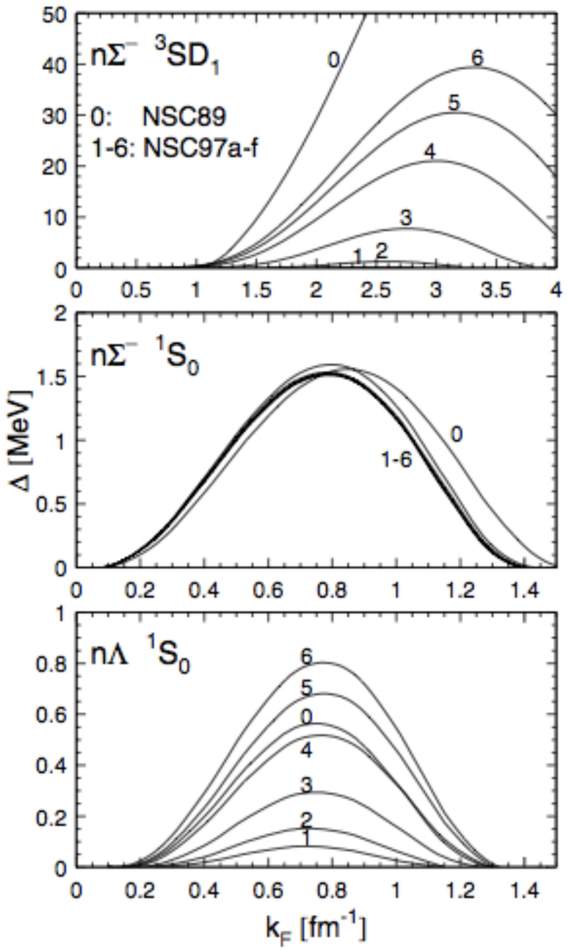
(Schaab, Shaffner-Bielich & Balberg 1998)



R: relative emissitivy w.r.t. nucleonic DURCA

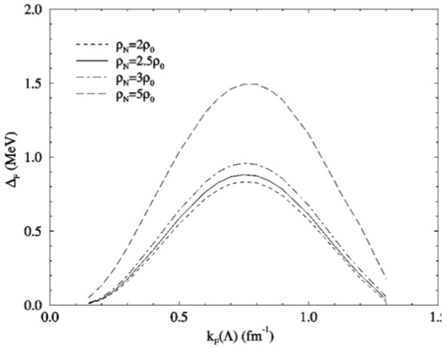
Pairing Gap → suppression of C_v & ε by $\sim e^{(-\Delta/k_BT)}$

- $^1S_0$, $^3SD_1$ ΣN & $^1S_0$ ΛN gap

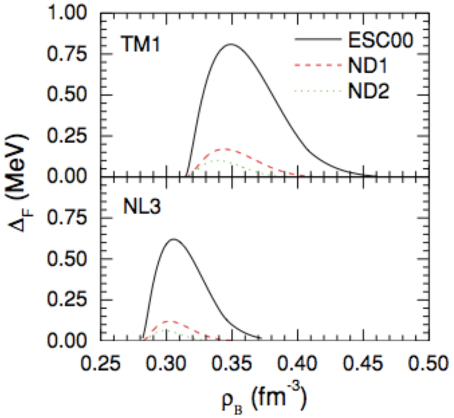


(Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0$ ΛΛ gap

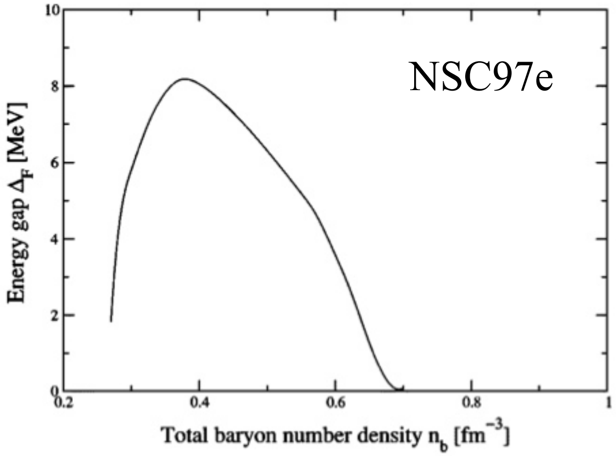


(Balberg & Barnea 1998)

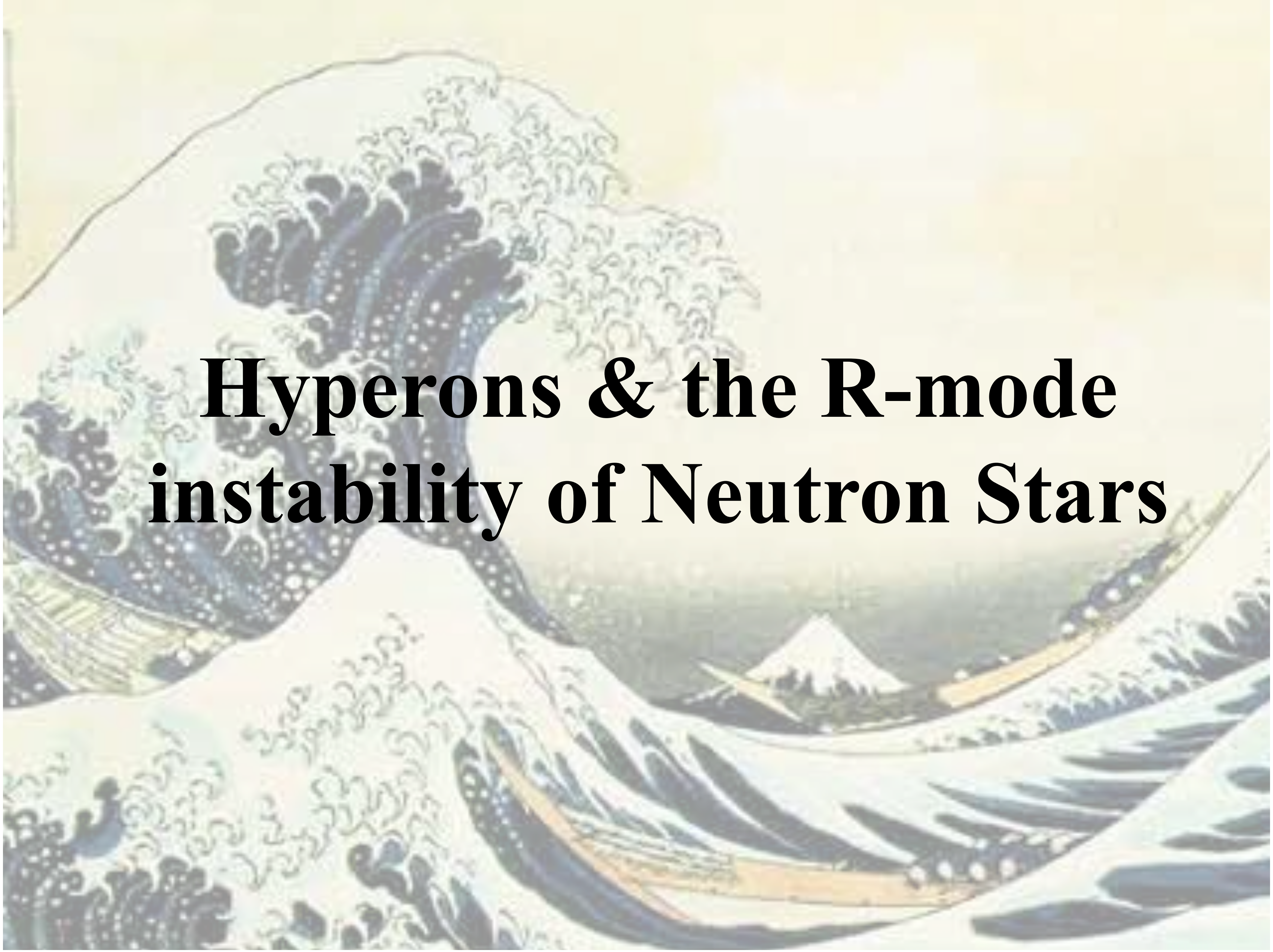


(Wang & Shen 2010)

- $^1S_0$ ΣΣ gap



(IV & Tolós 2004)

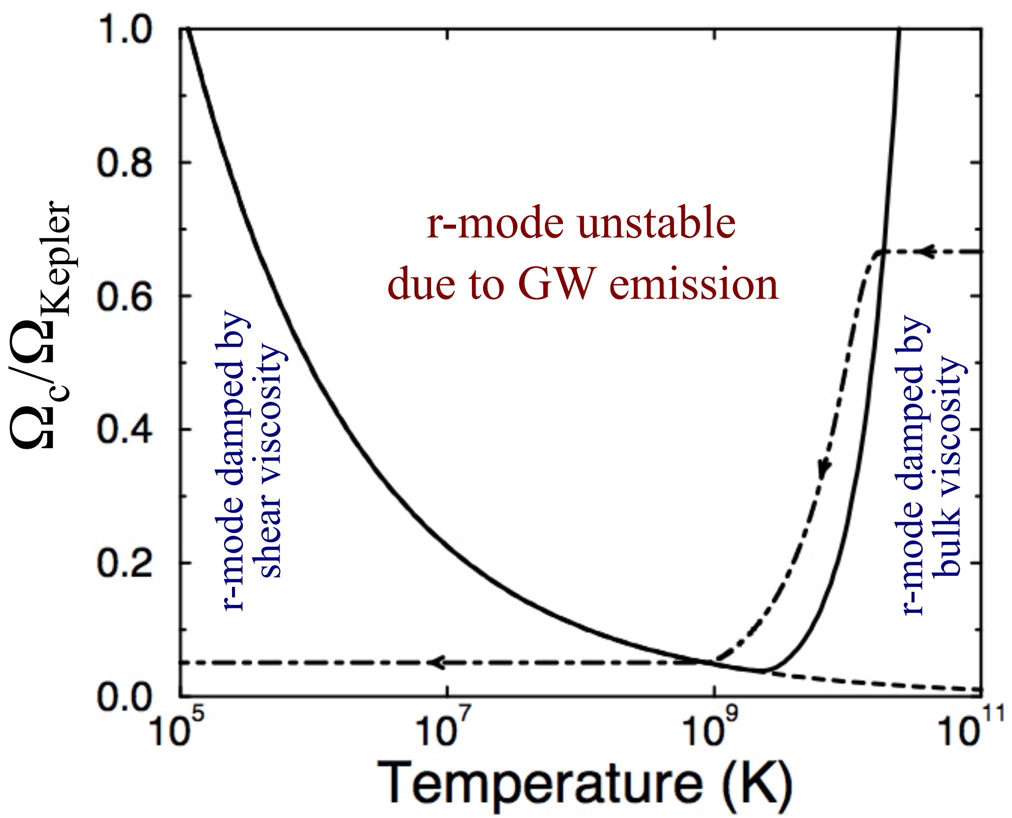


Hyperons & the R-mode instability of Neutron Stars

The r-mode Instability

Ω_{Kepler} : Absolute Upper Limit of Rot. Freq.

Instabilities prevent NS to reach Ω_{Kepler}



r-mode Instability : toroidal mode of oscillation

✓ restoring force: Coriolis

✓ emission of GW in hot & rapidly rotating NS (CFS mechanism)

- GW makes the mode unstable
- Viscosity stabilizes the mode

$$A \propto A_0 e^{-i\omega(\Omega) - t/\tau(\Omega,T)}$$

$$\frac{1}{\tau(\Omega,T)} = -\frac{1}{\tau_{GW}(\Omega)} + \frac{1}{\tau_{Viscosity}(\Omega,T)}$$

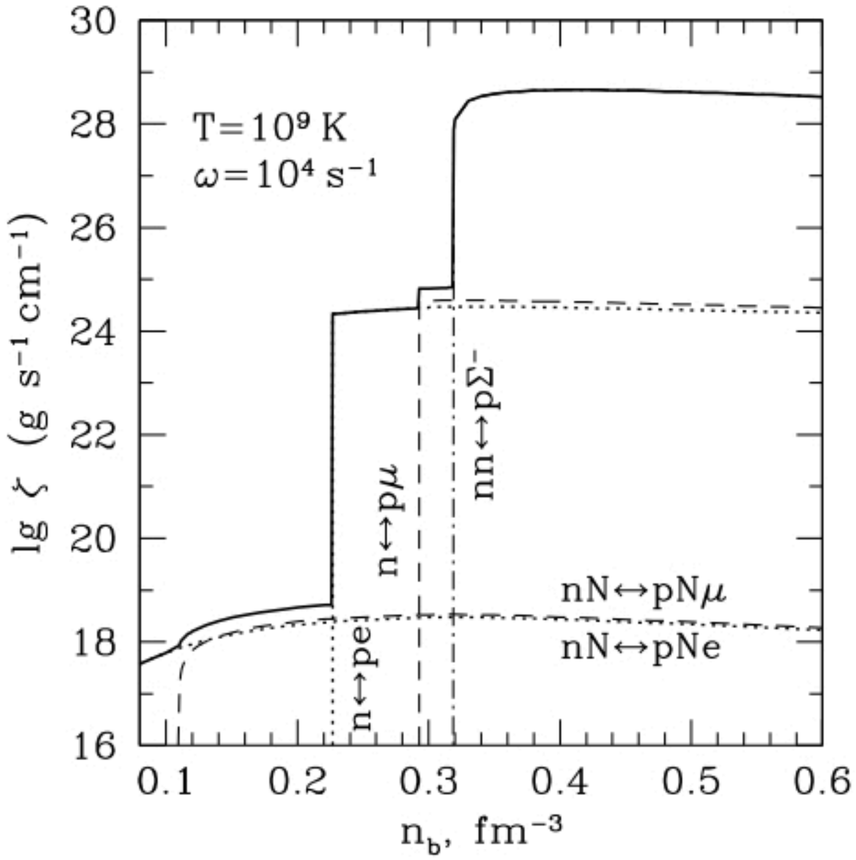
Hyperon Bulk Viscosity ξ_Y

(Lindblom et al. 2002, Haensel et al 2002, van Dalen et al. 2002, Chatterjee et al. 2008, Gusakov et al. 2008, Shina et al. 2009, Jha et al. 2010,…)

Sources of ξ_Y:

non-leptonic weak reactions	$N+N \leftrightarrow N+Y$ $N+Y \leftrightarrow Y+Y$
Direct & Modified URCA	$Y \rightarrow B+l+\bar{\nu}_l$ $B'+Y \rightarrow B'+B+l+\bar{\nu}_l$
strong reactions	$N+Y \leftrightarrow N+Y$ $N+\Xi \leftrightarrow Y+Y$ $Y+Y \leftrightarrow Y+Y$

(Haensel, Levenfish & Yakovlev 2002)



Reaction Rates & ξ_Y reduced by Hyperon Superfluidity

Critical Angular Velocity of Neutron Stars

- r-mode amplitude: $A \propto A_o e^{-i\omega(\Omega)t - t/\tau(\Omega)}$

$$\frac{1}{\tau(\Omega,T)} = -\frac{1}{\tau_{GW}(\Omega)} + \frac{1}{\tau_{\xi}(\Omega,T)} + \frac{1}{\tau_{\eta}(T)}$$

→ $\frac{1}{\tau(\Omega_c,T)} = 0$ r-mode instability region

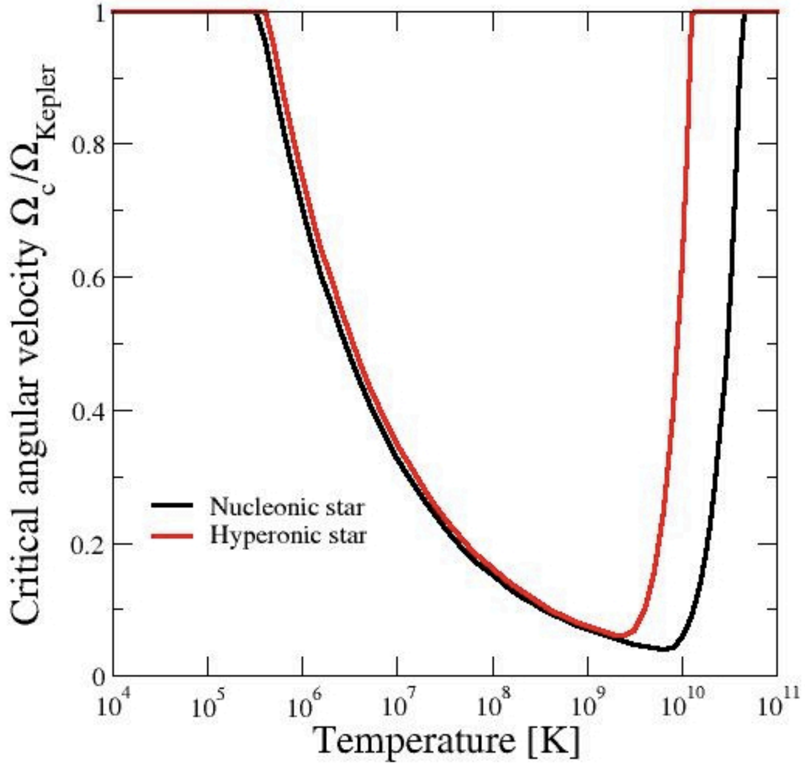
$\Omega < \Omega_c$ stable

$\Omega > \Omega_c$ unstable

As expected:

smaller r-mode instability region due to hyperons

(I.V. & C. Albertus in preparation)



BHF: NN (Av18)+NY (NSC89)
(M=1.27$M_\odot$)

Take away message

Hyperons in Neutron Stars

- ✓ Strong softening of EoS & reduction of NS Mass
  - ➔ Hyperons & Massive NS still an open question
- ✓ Modification of PNS properties (composition, EoS, Mass)
- ✓ Additional Fast Cooling Processes
- ✓ Reduction of r-mode instability region

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