Do hyperons exist in the interior of neutron stars ?

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In this talk …

I will review the role of hyperons on :

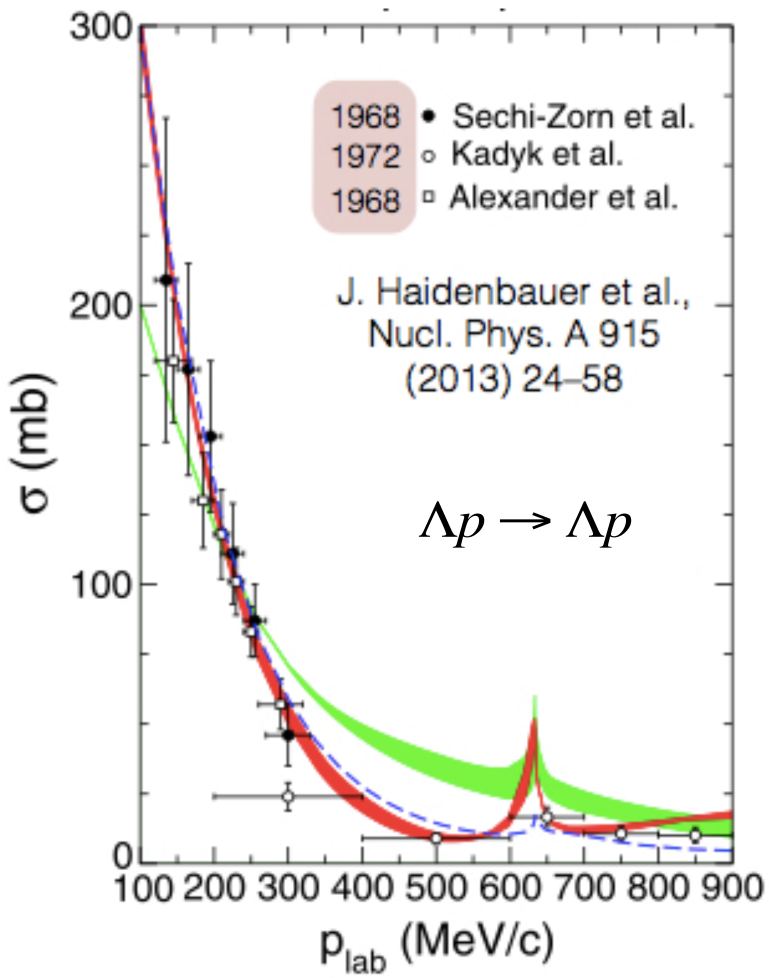
- ❖ EoS & M_{max} of Neutron Stars
  (hyperon puzzle & possible solutions)
- ❖ Neutron Star Cooling
- ❖ r-mode instability of Neutron Stars

For details see:

D. Chatterjee. & I.V. EPJA 52, 29 (2016)

What do we know to include hyperons in the EoS ?

Unfortunately, much less than in the pure nucleonic sector
to put stringent constraints on the YN & YY interactions

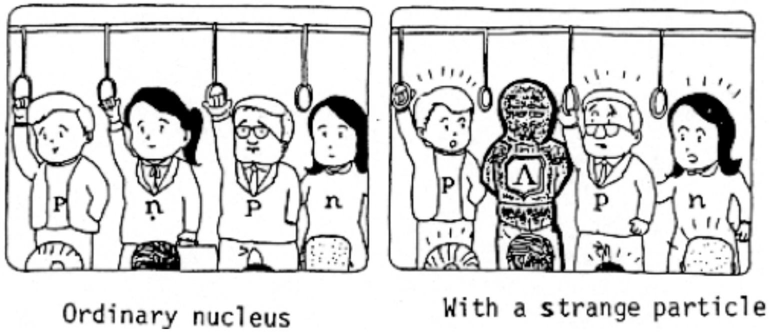


- Very few YN scattering data due to short lifetime of hyperons & low intensity beam fluxes
  - ~ 35 data points, all from the 1960s
  - 10 new data points, from KEK-PS E251 collaboration (2000)
- No YY scattering data exists

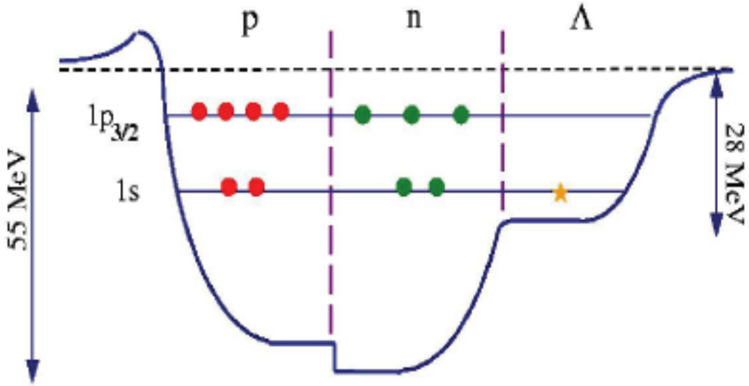
(cf. > 4000 NN data for $E_{lab} < 350$ MeV)

➢ Alternative information can be obtained from hypernuclei

- ✧ A hypernucleus is a bound system of nucleons with one or more strange baryons ($\Lambda, \Sigma, \Xi, \Omega^-$ hyperons).



H. Bando, PARITY 1, 54 (1986)

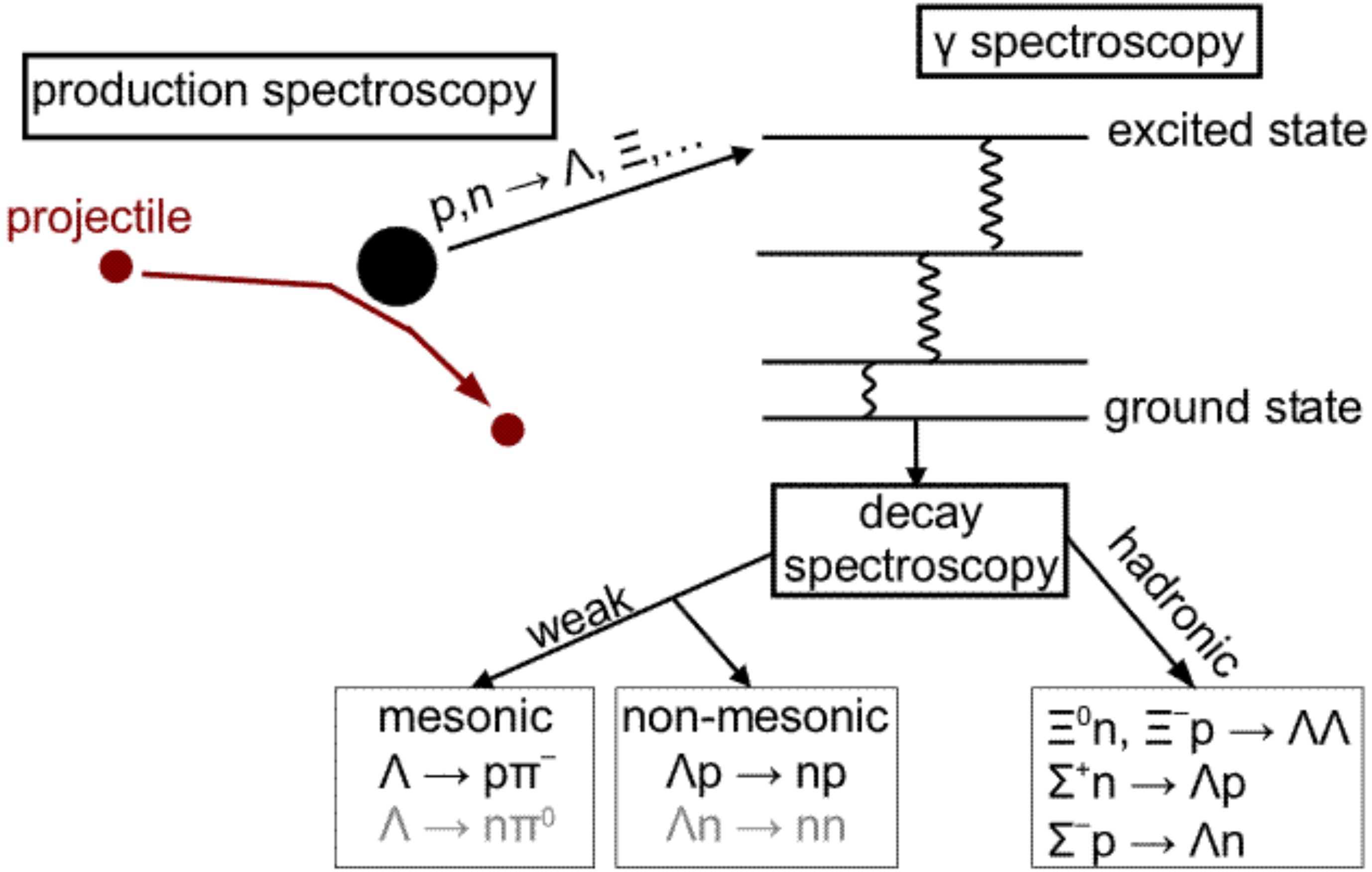


Simple s.p. model of $^{12}_{\Lambda}C$

- ✧ In a simple single-particle model: protons, neutrons and hyperons are considered distinguishable particles placed in independent effective potential wells in which Pauli exclusion principle is applied.

Hypernuclear Physics in a Nutshell

Goal: Relate hypernuclear observables with the bare YN & YY interactions



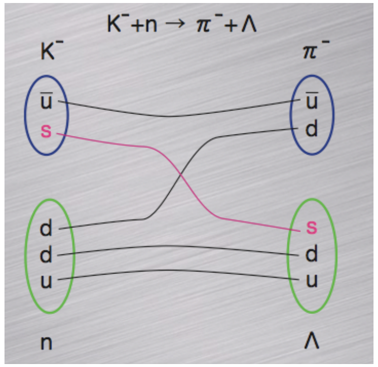
Production of Λ hypernuclei can occur by …

✧ Strangeness exchange: (BNL, KEK, JPARC)

(replace a u or d quark with an s quark)

$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

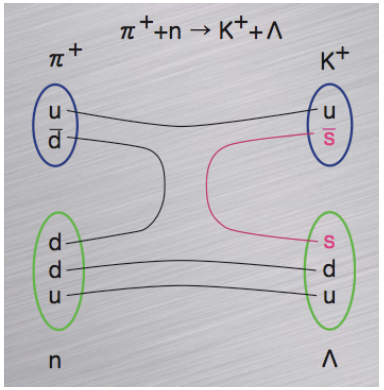
Where the K^- in-flight or stopped



✧ Associated production: (BNL, KEK, GSI)

(produces an $s\bar{s}$ pair)

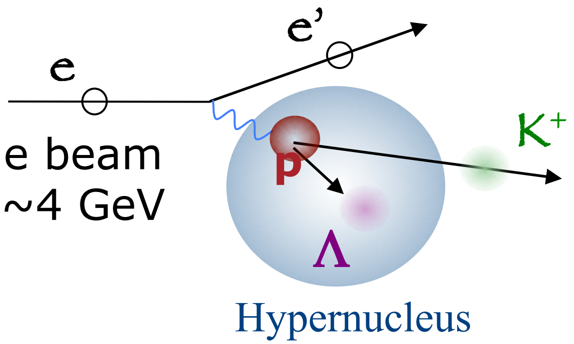
$$\pi^+ + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^+$$



- Electroproduction: (JLAB, MAMI-C)

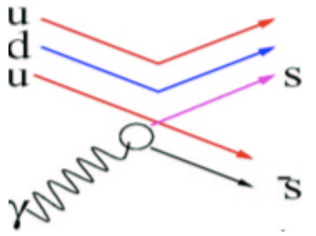
$$e^- + {}^{A}Z \rightarrow e^{-\prime} + K^+ + {}^{A}_{\Lambda}(Z-1)$$

${}^{A}Z(e,e'K){}^{A}(Z-1)_{\Lambda}$



elementary process

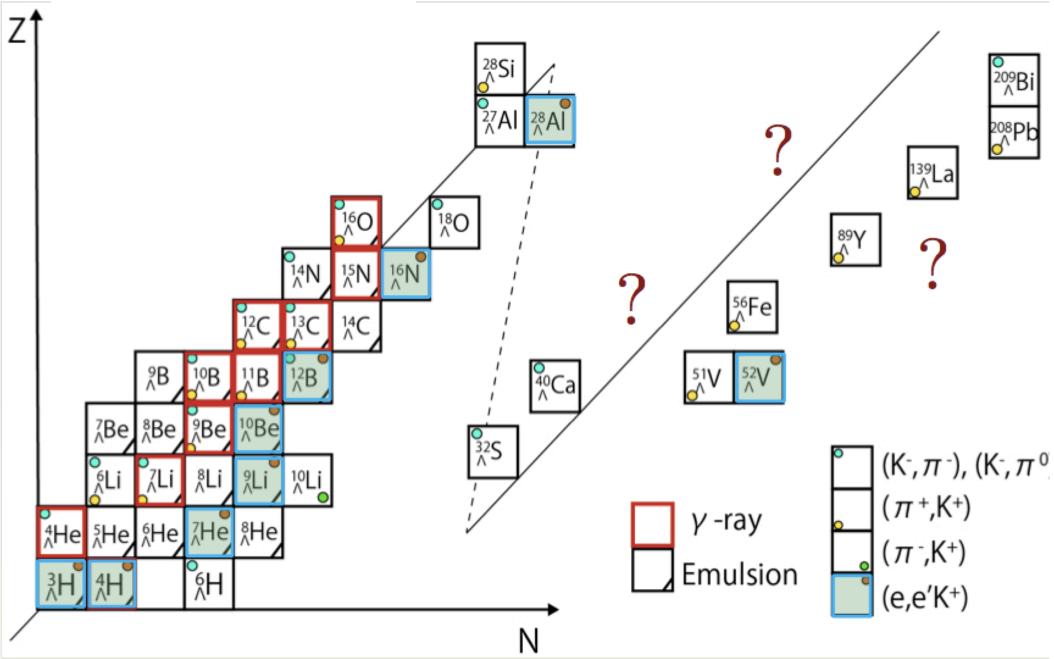
$$\gamma + p \rightarrow \Lambda + K^+$$



- New: Hypernuclei production in RHIC (FAIR/GSI). First experiment with ^{6}Li beam on ^{12}C target at 2GeV. Λ, ${}^{3}_{\Lambda}$H & ${}^{4}_{\Lambda}$H observed.

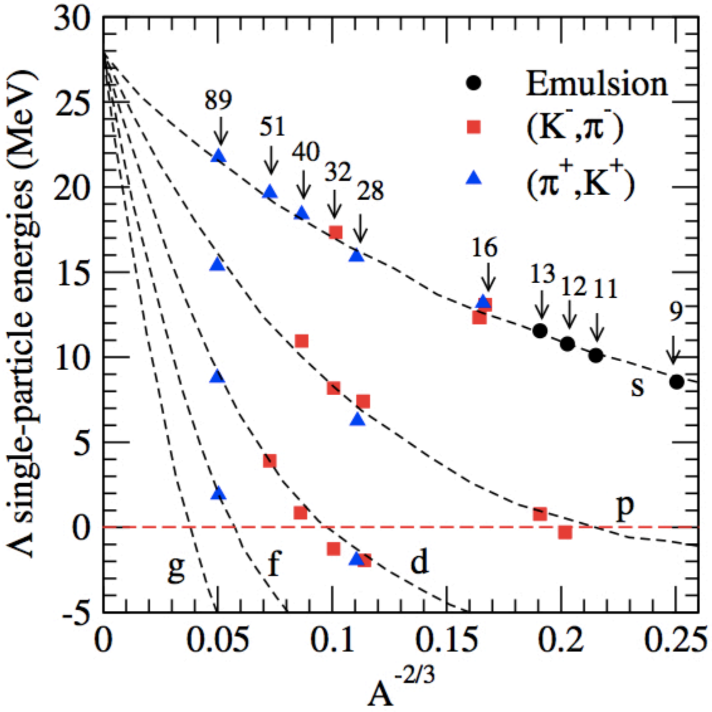
Present status of Λ Hypernuclear Spectroscopy

Λ Hypernuclear Chart (2014)



S. N. Nakamura, Hypernuclear Workshop, Jlab 2014, updated from:
O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57, 564 (2006)

Λ s.p. energies



D. Chatterjee & I. V. (2016)

The production of double Λ hypernuclei

✧ Ξ^- conversion in two Λ's:

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5\, MeV$$

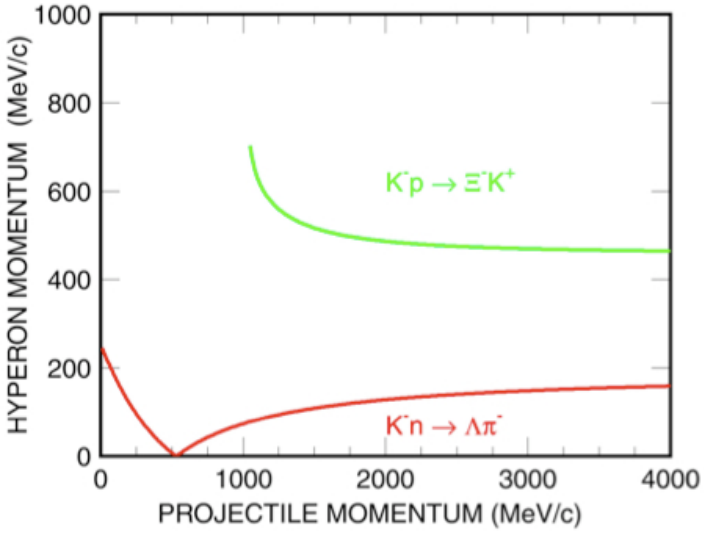
- Ξ^- production:

✓ (K^-,K^+) reaction (BNL, KEK)

$$K^- + p \rightarrow \Xi^- + K^+$$

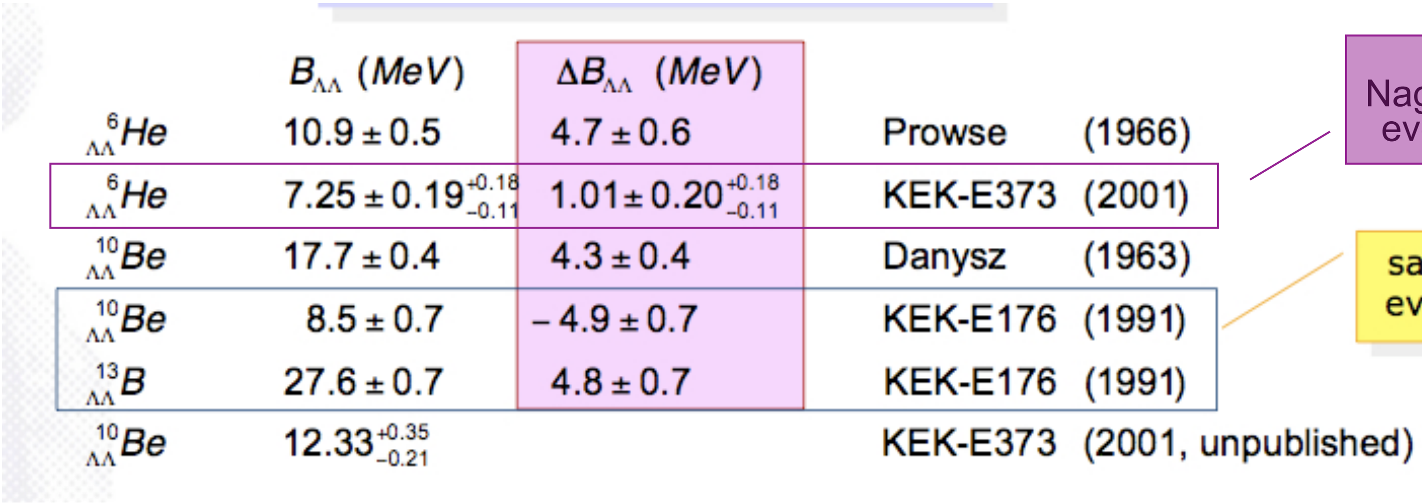
✓ Antiproton production (PANDA@FAIR)

$$p + \overline{p} \rightarrow \Xi^- + \overline{\Xi}^+$$



What do we know about double Λ hypernuclei ?

Not so much ….



	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)		
${}^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.7 ± 0.6	Prowse	(1966)
${}^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$	KEK-E373	(2001)
${}^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4	Danysz	(1963)
${}^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7	KEK-E176	(1991)
${}^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7	KEK-E176	(1991)
${}^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$		KEK-E373	(2001, unpublished)

Nagara event

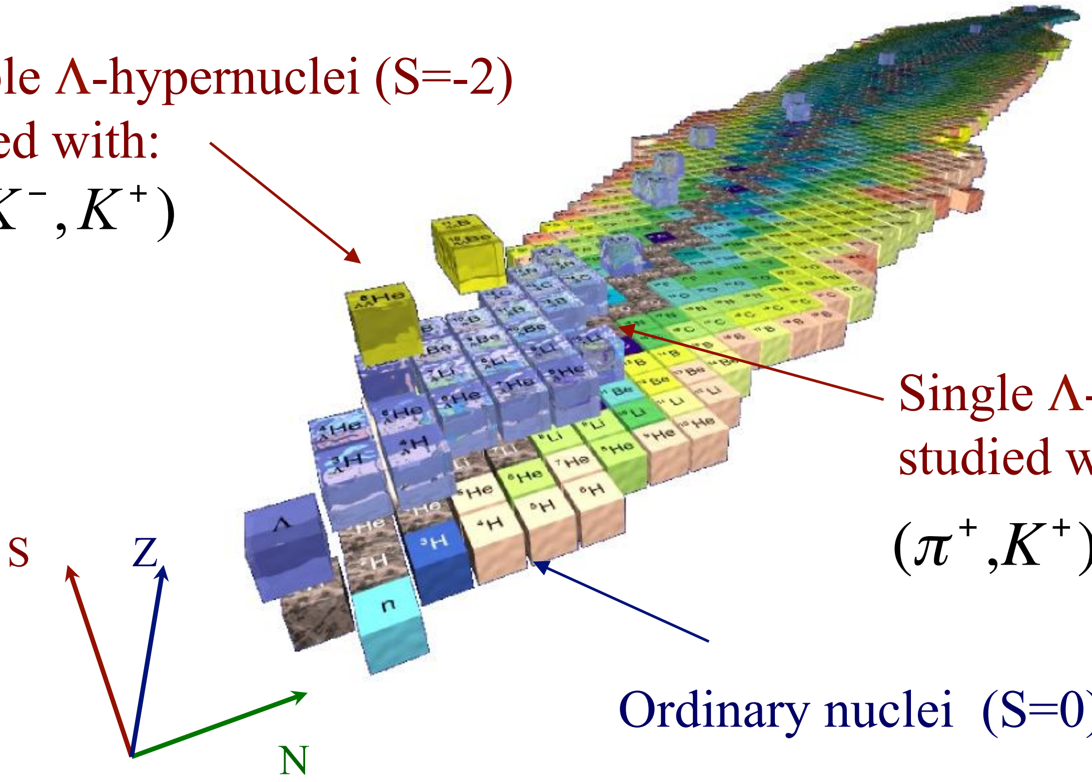
same event

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

Summary of our present knowledge & ignorance

- 41 single Λ-hypernuclei → ΛN attractive ($U_\Lambda(\rho_0) \sim -30$ MeV)
- 3 double-Λ hypernuclei → weak ΛΛ attraction ($\Delta B_{\Lambda\Lambda} \sim 1$MeV)
- Very few Ξ-hypernuclei → ΞN attractive ($U_\Xi(\rho_0) \sim -14$ MeV)
- Ambiguous evidence of Σ-hypernuclei → ΣN repulsive ($U_\Sigma(\rho_0) > +15$ MeV) ?



Double Λ-hypernuclei (S=-2)
studied with:
(K^-, K^+)

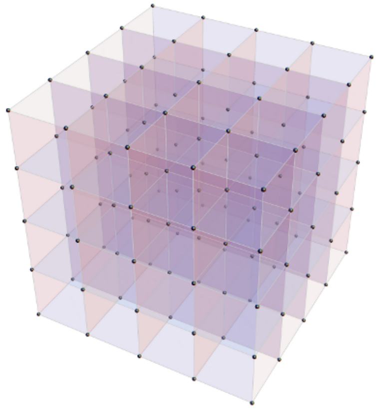
Single Λ-hypernuclei (S=-1)
studied with:
$(\pi^+, K^+), (K^-, \pi^-), (e, e'K^+)$

Ordinary nuclei (S=0)

Unfortunately, there are always problems …

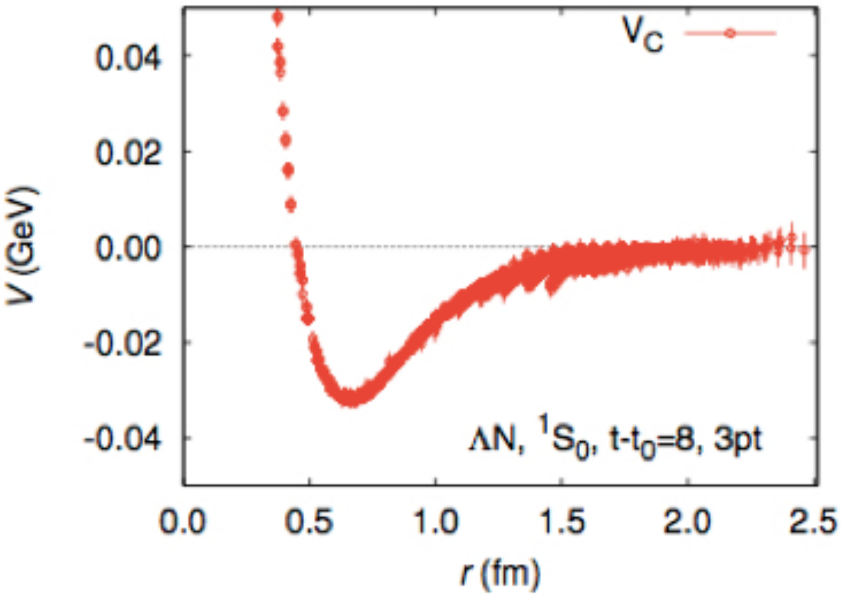
- ✧ Limited amount of scattering data not enough to fully constrain the bare YN & YY interactions ⟶ Strategy: start from a NN model & impose SU(3)$_f$ constraints to build YN & YY (e.g., Juelich & Nijmegen models)
- ✧ Bare YN & YY is not easy to derive from hypernuclei. Hyperons in nuclei are not free but in-medium. Hypernuclei provide effective hyperon-nucleus interactions
- ✧ Amount of experimental data on hypernuclei is not enough to constrain the uncertainties of phenomenological models. Parameters are most of the times arbitrarily chosen
- ✧ Ab-initio hypernuclear structure calculations with bare YN & YY interactions exists but are less accurate than phenomenological ones due to the difficulties to solve the very complicated nuclear many-body problem

Lattice QCD

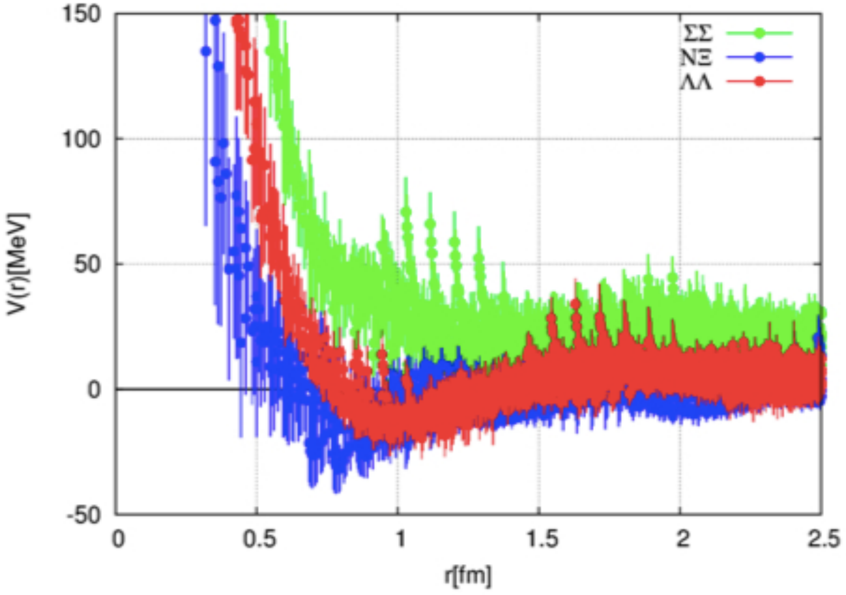


Lattice QCD calculations can provide the much required YN, YY & hyperonic TBFs.

ΛN (I=0) $^1S_0$ (m_π=570 MeV)



$\Lambda\Lambda$, $N\Xi$ & $\Sigma\Sigma$ (I=0) $^1S_0$ (m_π=145 MeV)



Hal QCD collaboration, HYP2015

Shopping List

We need:

✧ More & updated hypernuclear data (FAIR, JLAB, J-PARC)

✧ Measurements of multi-strange hypernuclei (FAIR)

✧ Study of light hypernuclei (role of hyperonic TBFs)

✧ More YN and (hopefuly) YY scattering data

✧ Lattice QCD calculations

✧ Analysis of hyperon-hyperon correlations in HIC

✧ Astronomical data sensitive to the strangeness content of NS

Hyperons in Neutron Stars

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

Phenomenological approaches

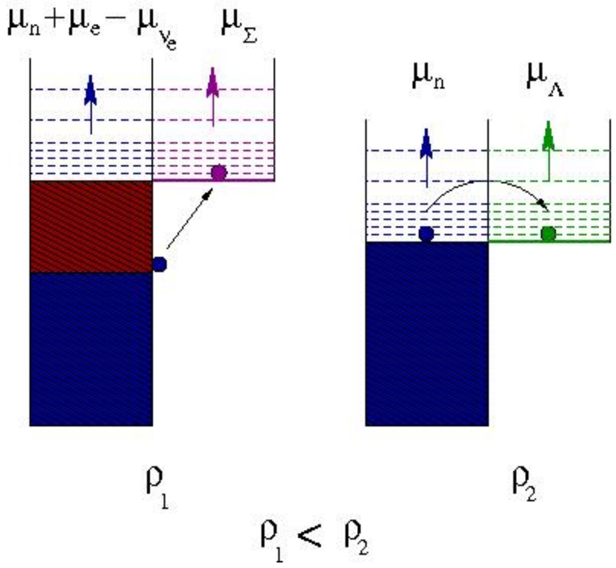
- Relativistic Mean Field Models: Glendenning 1985; Knorren et al. 1995; Shaffner-Bielich & Mishustin 1996, Bonano & Sedrakian 2012, …
- Non-realtivistic potential model: Balberg & Gal 1997
- Quark-meson coupling model: Pal et al. 1999, …
- Chiral Effective Lagrangians: Hanauske et al., 2000
- Density 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)
- $V_{\text{low k}}$: Djapo, Schaefer & Wambach, 2010
- Quantum Monte Carlo: Lonardoni et al., (2014)

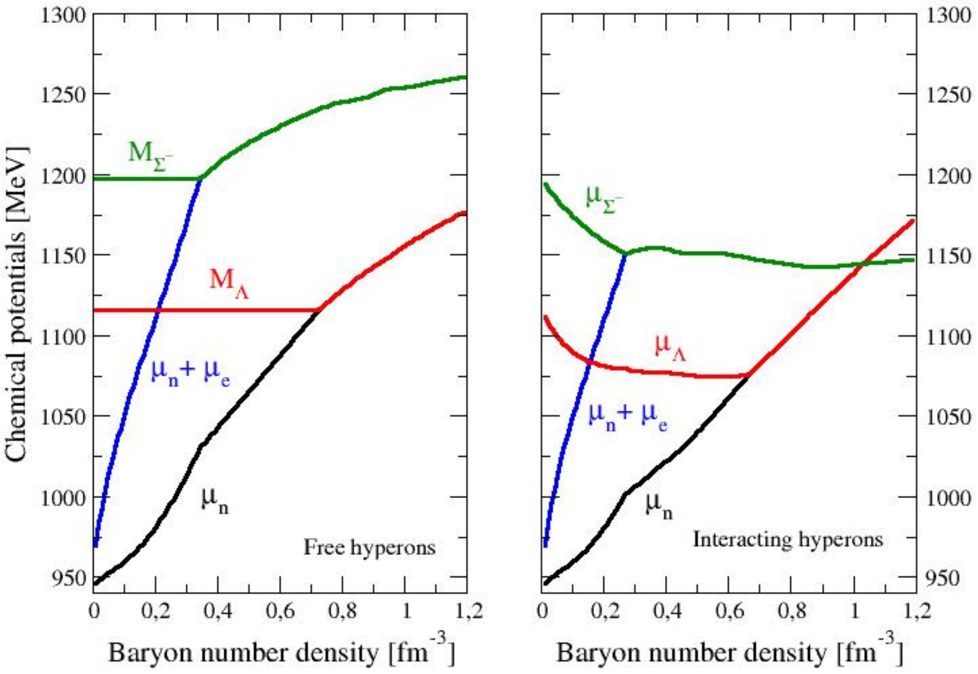
Sorry if I missed somebody

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.



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

$$\mu_\Lambda = \mu_n$$



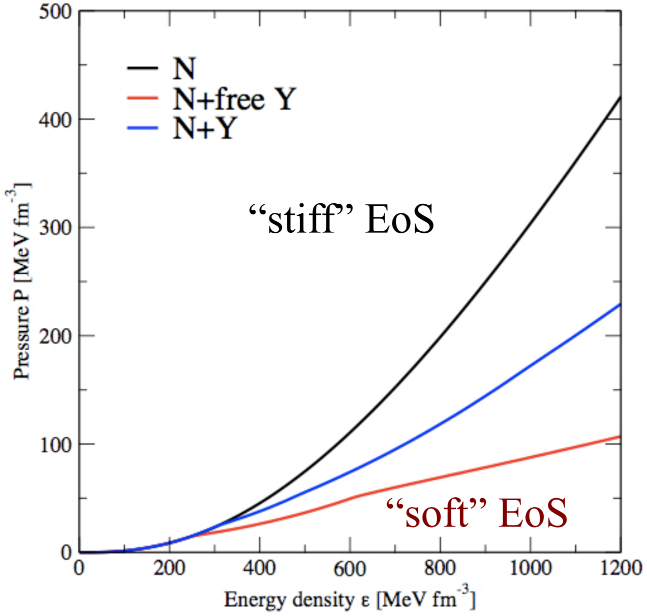
$$n + n \rightarrow n + \Lambda$$

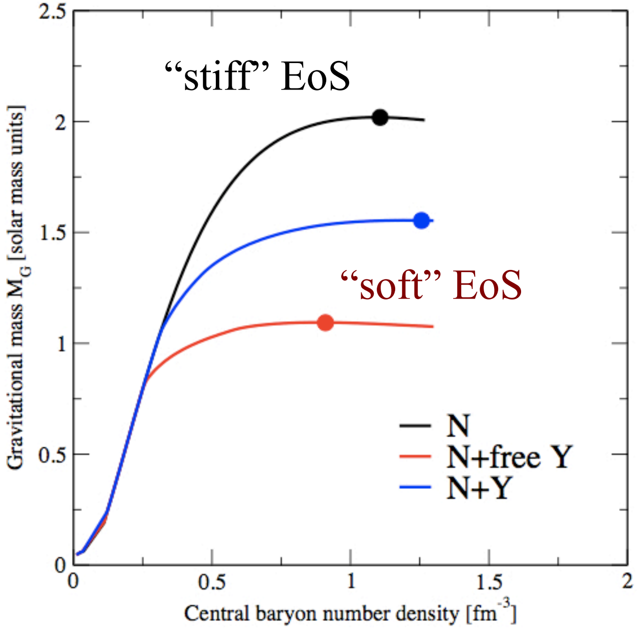
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

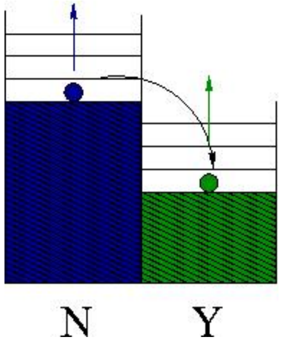
$$n + n \rightarrow p + \Sigma^-$$

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

Effect of Hyperons in the EoS and Mass of Neutron Stars



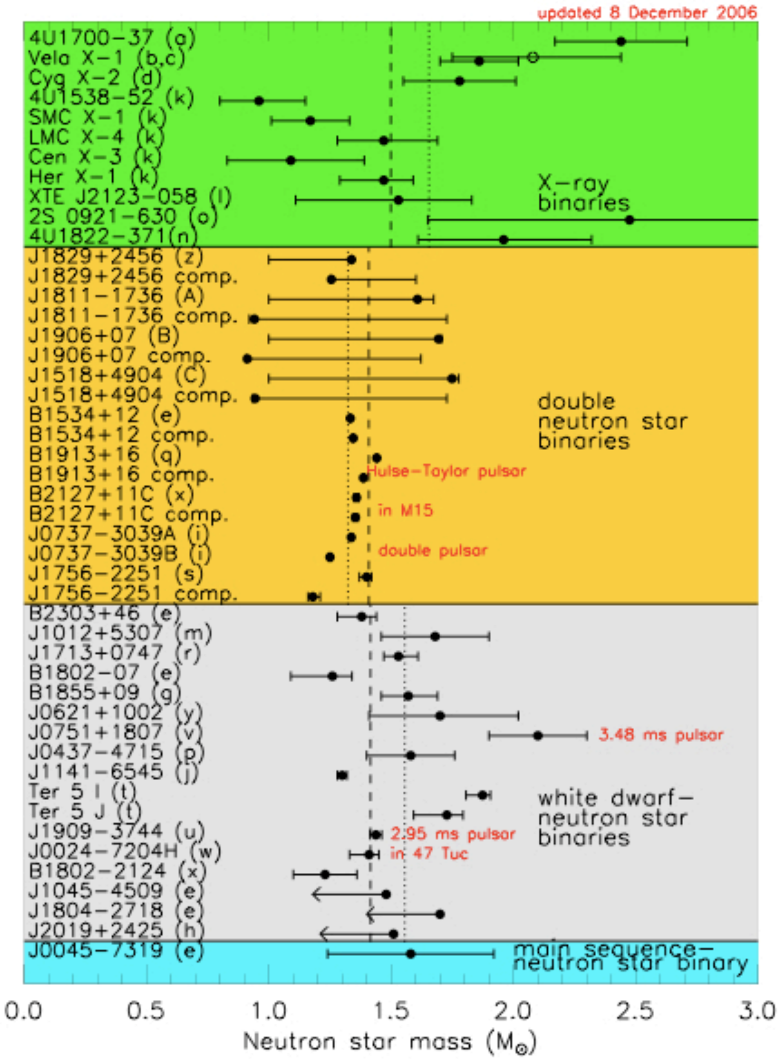




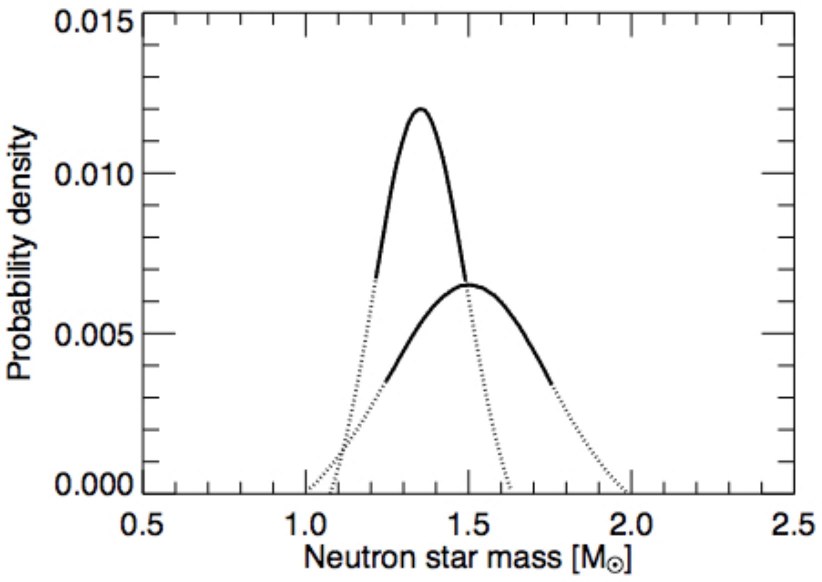
Relieve of Fermi pressure due to the appearance of hyperons ➔

EoS softer ➔ reduction of the mass

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



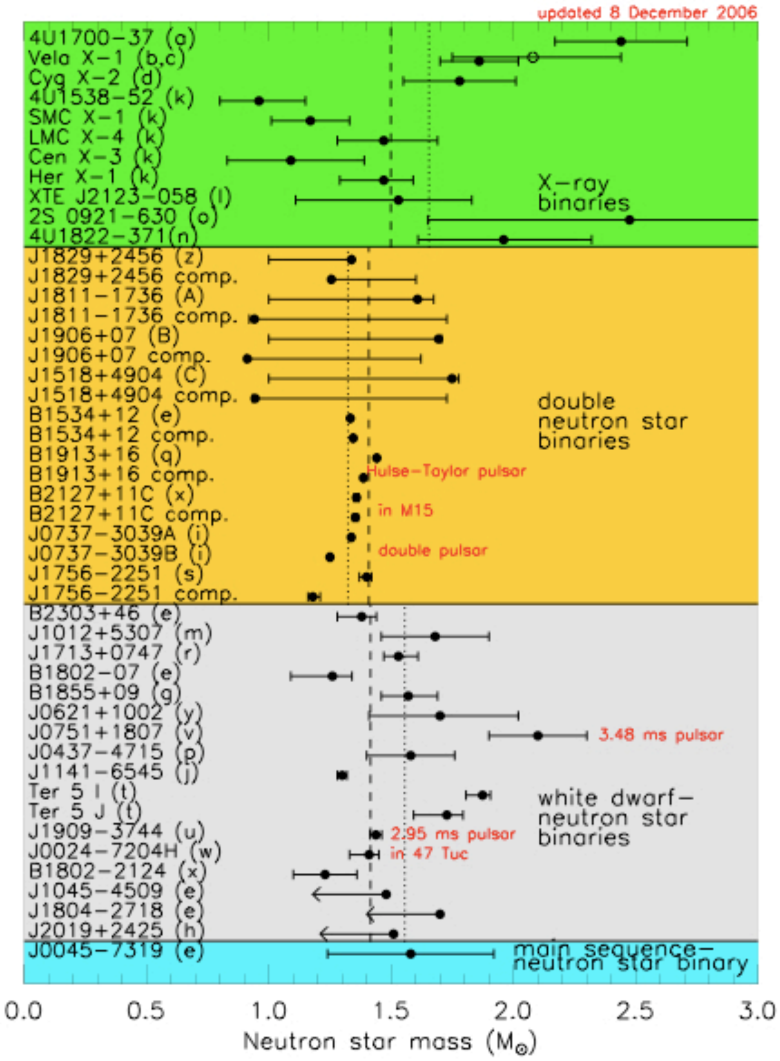
(Lattimer & Prakash 2007)



up to ~ 2006-2008 any valid EoS should predict

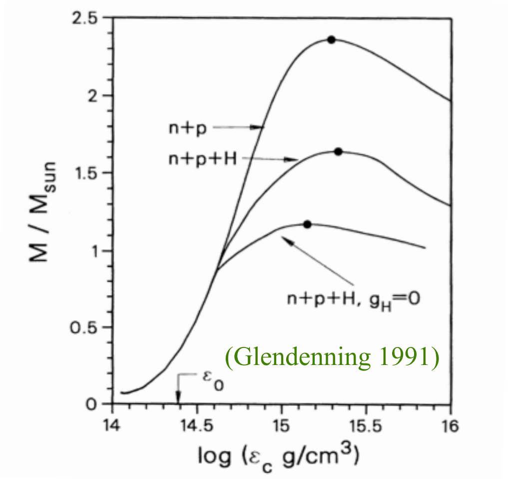
$$M_{\max}[EoS] > 1.4 - 1.5 M_\odot$$

Hyperons in NS
(up to ~ 2006-2008)



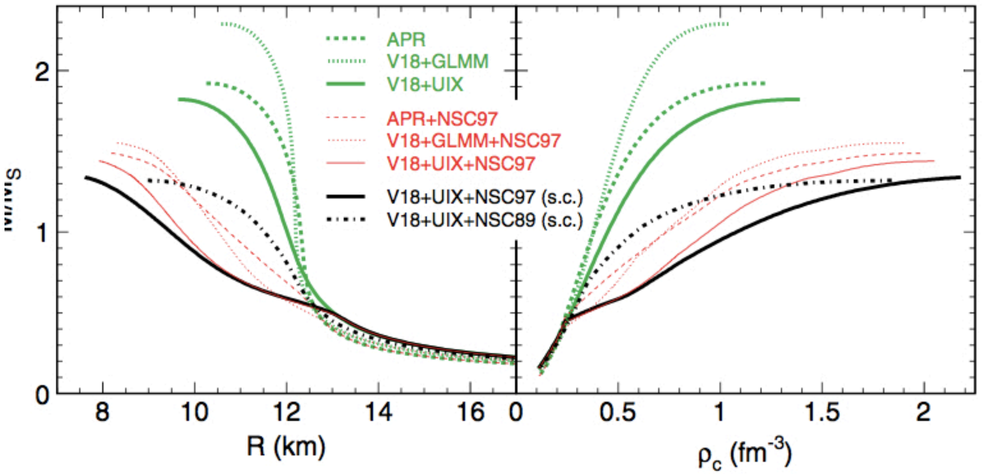
(Lattimer & Prakash 2007)

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 (and theoretitians) more difficult

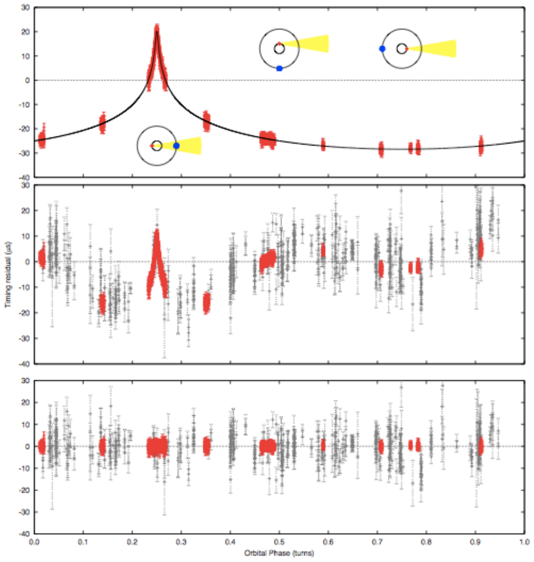
- <u>PSR J164-2230</u> (Demorest et al. 2010)

✓ binary system (P=8.68 d)

✓ low eccentricity ($\varepsilon=1.3 \times 10^{-6}$)

✓ companion mass: $\sim 0.5 M_\odot$

✓ pulsar mass: $M = 1.928 \pm 0.017 M_\odot$



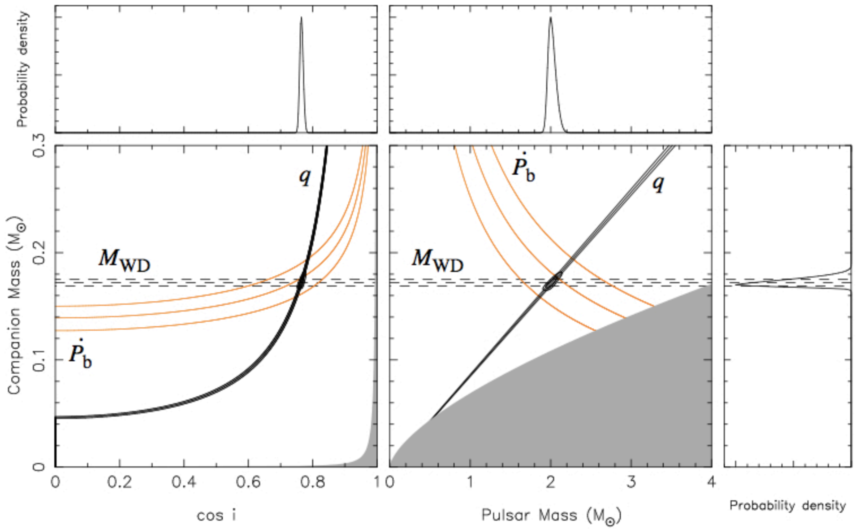
- <u>PSR J0348+0432</u> (Antoniadis et al. 2013)

✓ binary system (P=2.46 h)

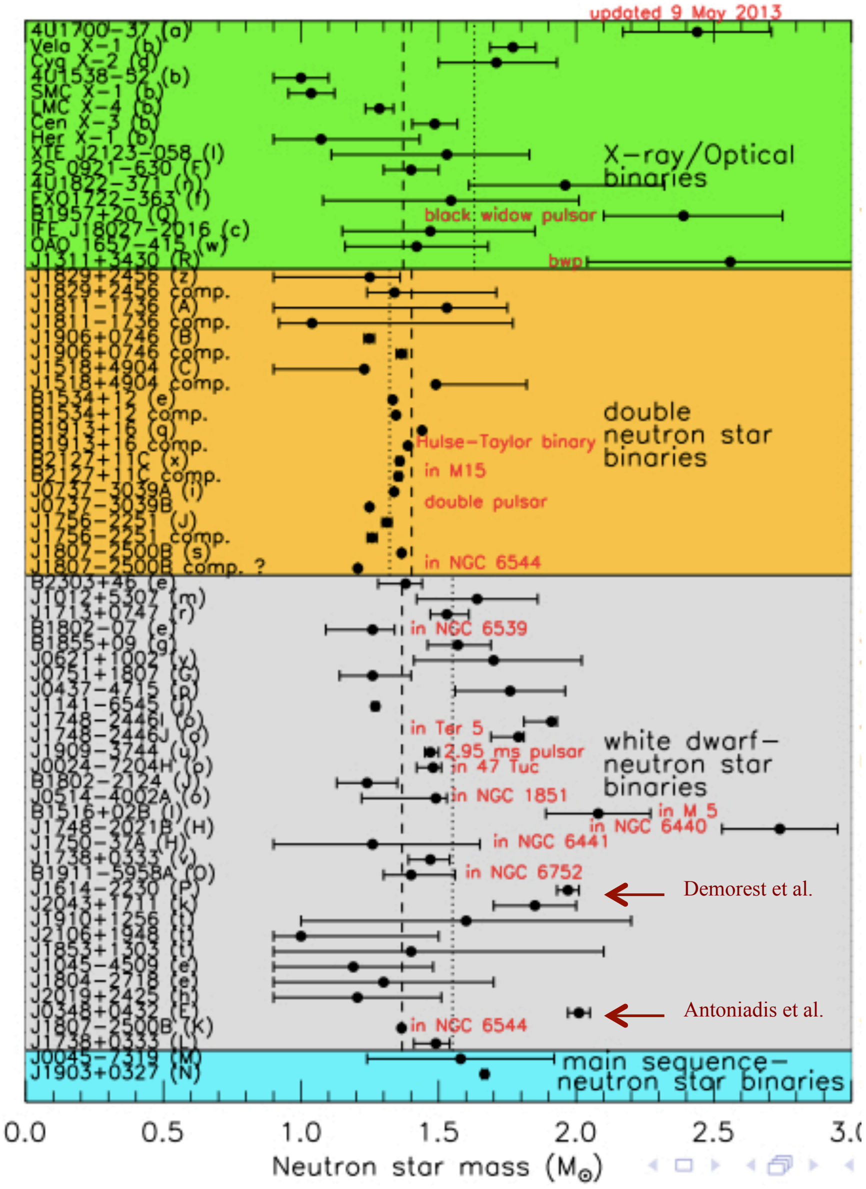
✓ very low eccentricity

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

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



Measured Neutron Star Masses (2017)



updated from Lattimer 2013

Observation of ~ 2 $M_\odot$ neutron stars

↓

Dense matter EoS stiff enough is required such that

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

A natural question arises:

Can hyperons, or strangeness in general, 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."

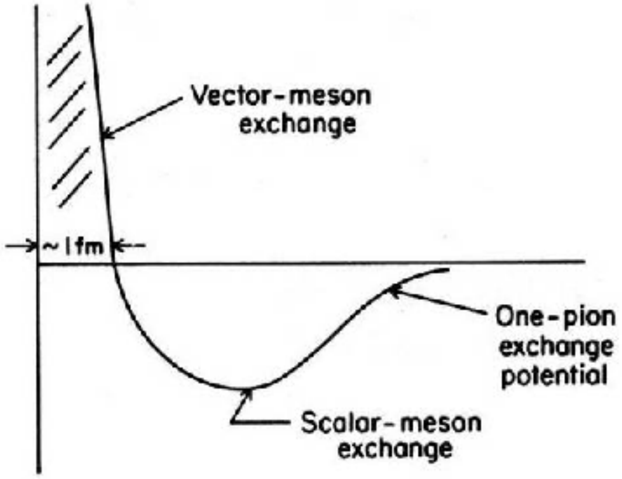
- ✓ can YN & YY interactions still solve it ?
- ✓ or perhaps hyperonic three-body forces ?
- ✓ what about quark matter ?

Solution I: YY vector meson repulsion

(explored in the context of RMF models)

General Feature:

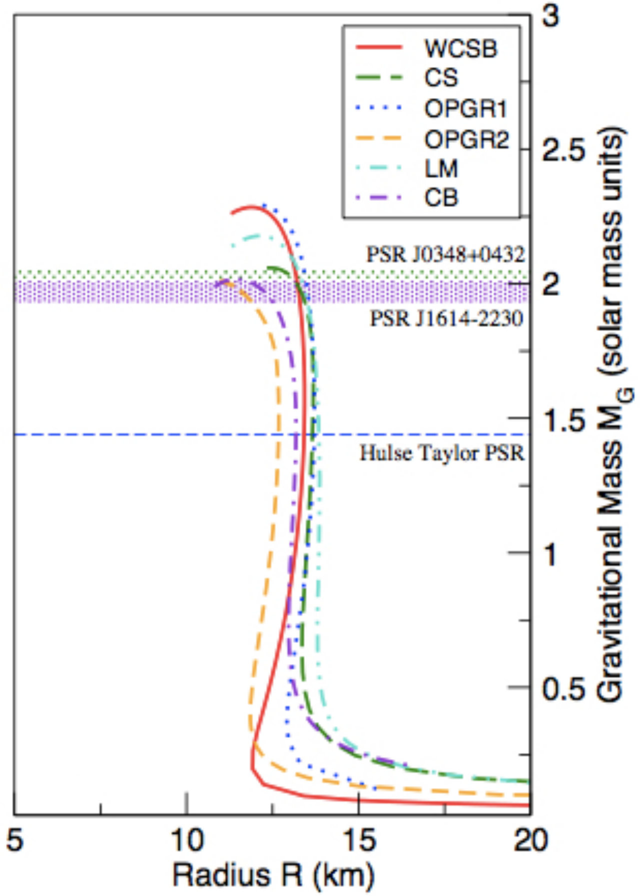
Exchange of scalar mesons generates attraction (softening), but the exchange of vector mesons generates repulsion (stiffening)



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)

Although some of these models are able to reconcile the presence of hyperons in the NS interior with the existence of 2M$_\odot$ NS, one must be cautious !!



D. Chatterjee & I. V. (2016)

✧ These models contain several free parameters which most of the times are arbitrarily chosen being the only jutification our still "scarce" knowledge of the YY interaction.

Hence:

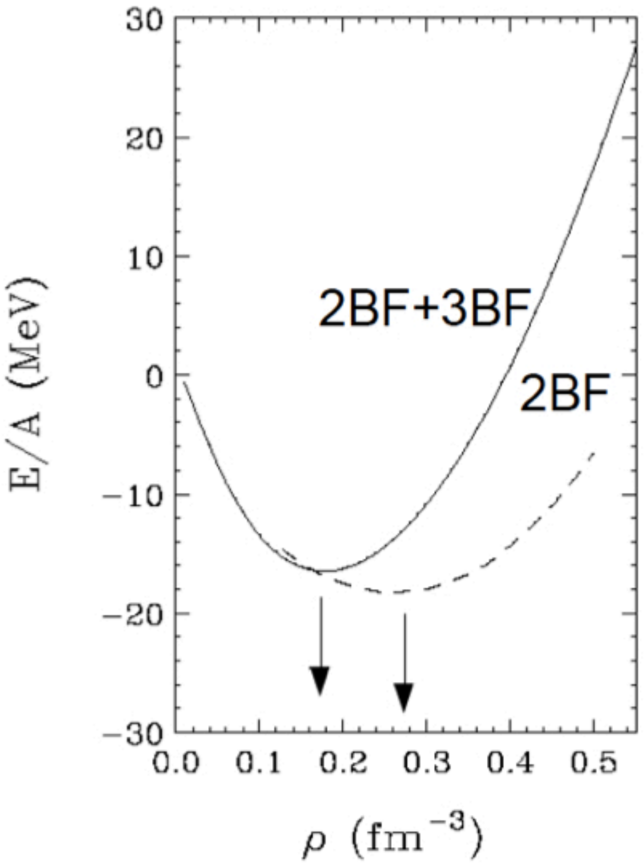
In absence of sufficient experimental data on multi-strange hypernuclei and YY scattering the validity of these models is still questionable.

Solution II: can Hyperonic TBF solve this puzzle ?

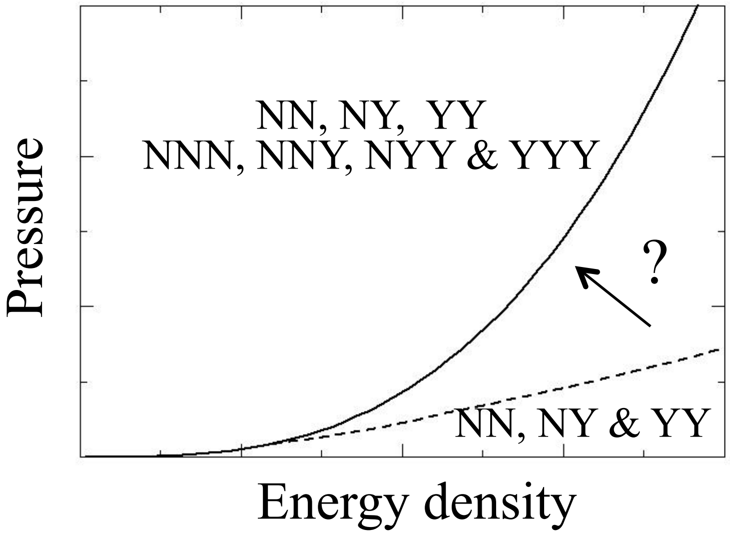
Natural solution based on: Importance of NNN force in Nuclear Physics

(Considered by several authors: Chalk, Gal, Usmani, Bodmer, Takatsuka, Loiseau, Nogami, Bahaduri, IV)

NNN Force

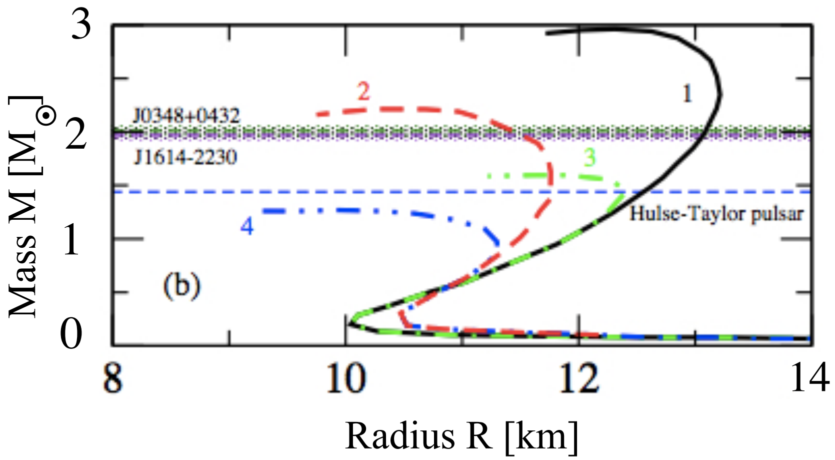


NNY, NYY & YYY Forces



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

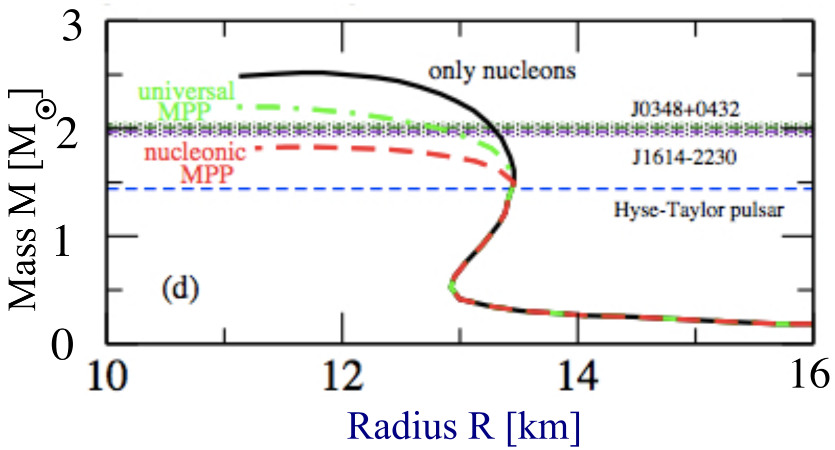
The results are contradictory



I. V. et al. (2011)

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

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

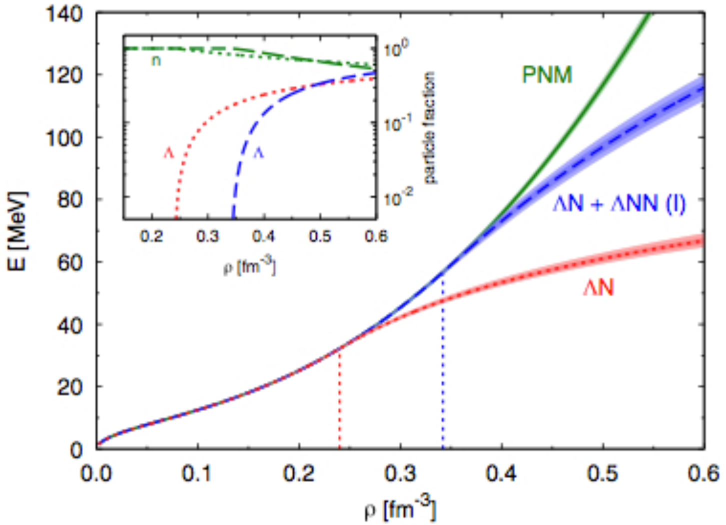


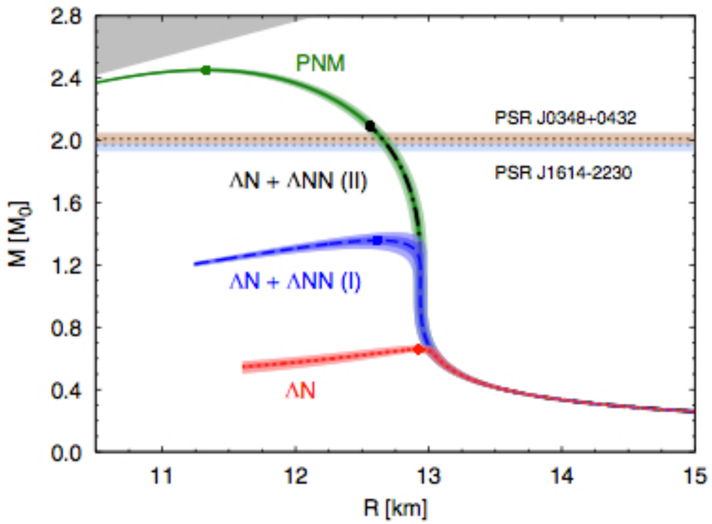
Yamamoto et al. (2015)

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

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

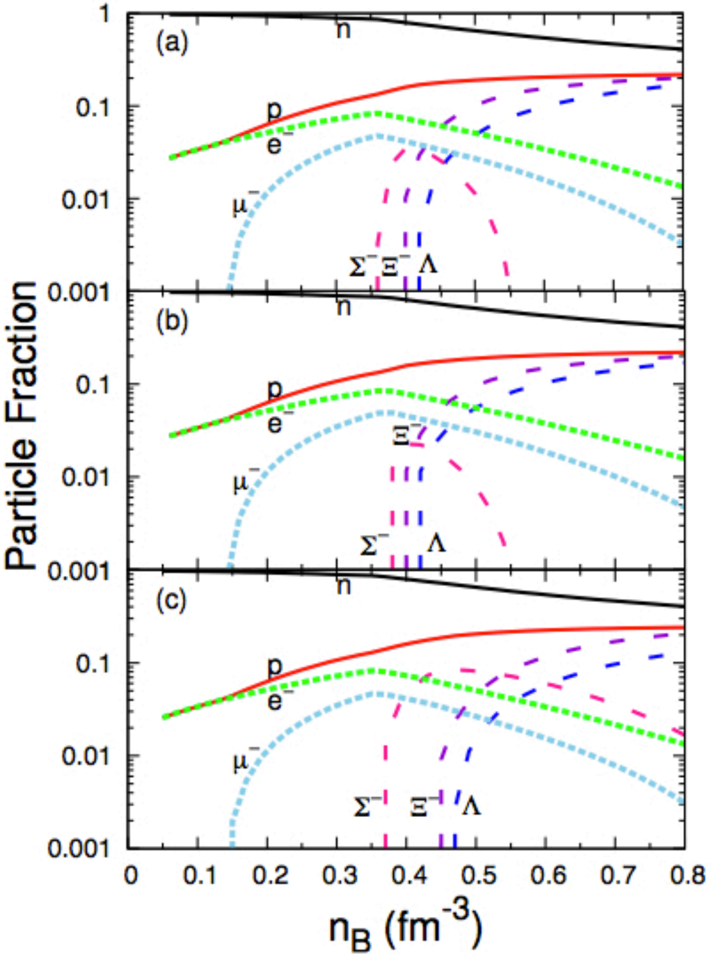
It should be mentioned also the recent Quantum Monte Carlo calculation by Lonardoni et al. (2015)

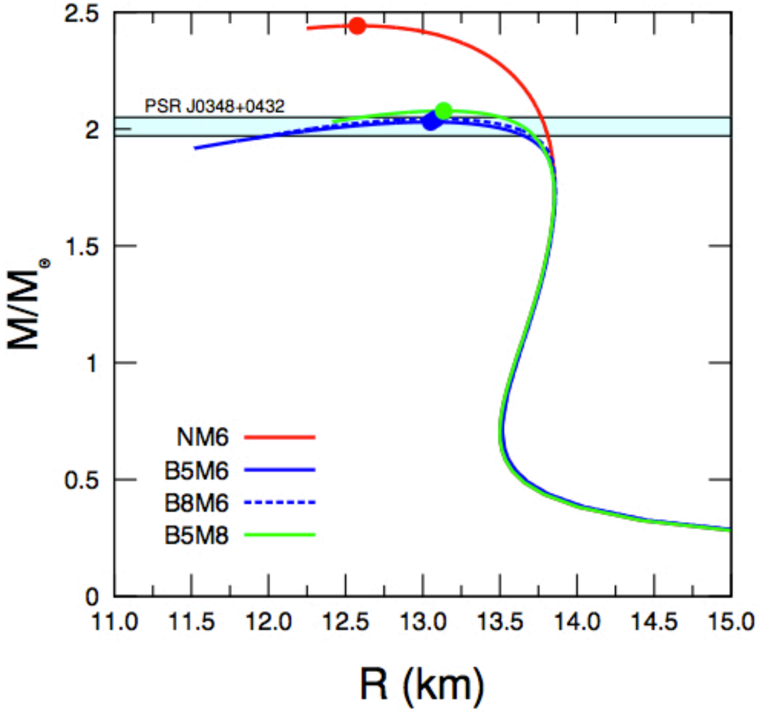




- First Quantum Monte Carlo calculation on neutron+Λ matter
- Strong dependence of Λ onset on Λnn force
- Some of the parametrizations of the Λnn force give maximum masses compatible with $2M_\odot$ but the onset of Λ is above the maximum density considered (~0.56 fm^{-3}). So in fact, no Λs are present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

and 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

Take Away Message

✧ It is still an open question whether hyperonic TBFs can, by themselves, solve completely the hyperon puzzle or not.

✧ It seems, however, that even if they are not the full solution, most probably they can contribute to it in an important way.

Solution III: Quark Matter Core

General Feature:

Some authors have suggested an early phase transition to deconfined quark matter as solution to the hyperon puzzle. 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 $\longrightarrow$ stiff EoS
- strong attraction in a channel $\longrightarrow$ strong color superconductivity

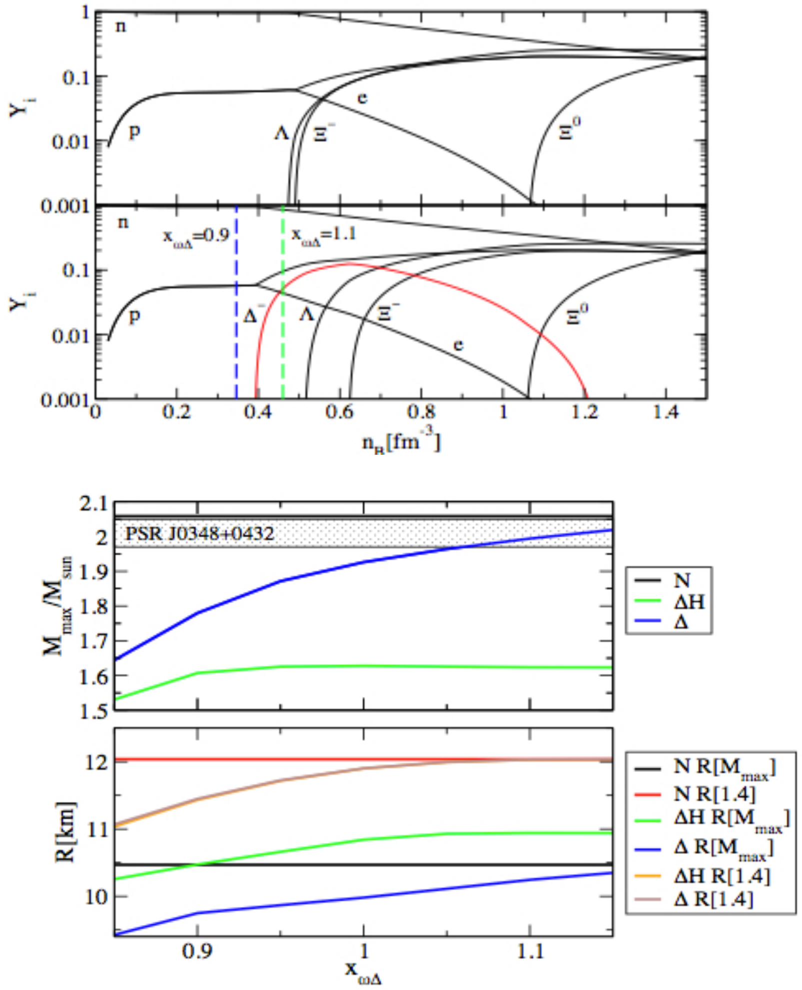
Ozel et al., (2010), Weissenborn et al., (2011), Klaehn et al., (2011), Bonano & Sedrakian (2012), Lastowiecki et al., (2012), Zdunik & Haensel (2012)

But also in this case we must pay attention

Currently theoretical descriptions of quark matter at high density rely on phenomenological models which are constrained using the few available experimental information on high density baryonic matter from heavy-ion collisions.

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

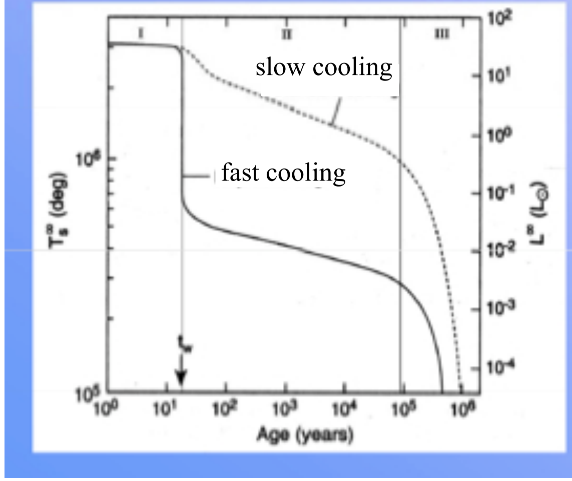
Hyperons & Neutron Star Cooling

Neutron Star Cooling in another Nutshell

Two cooling regimes

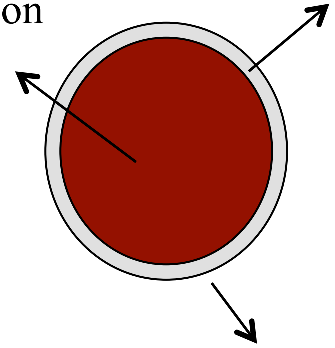
Slow
Low NS mass

Fast
High NS mass



I. Core relaxation epoch
II. Neutrino cooling epoch
III. Photon cooling epoch

Core cools by
neutrino emission

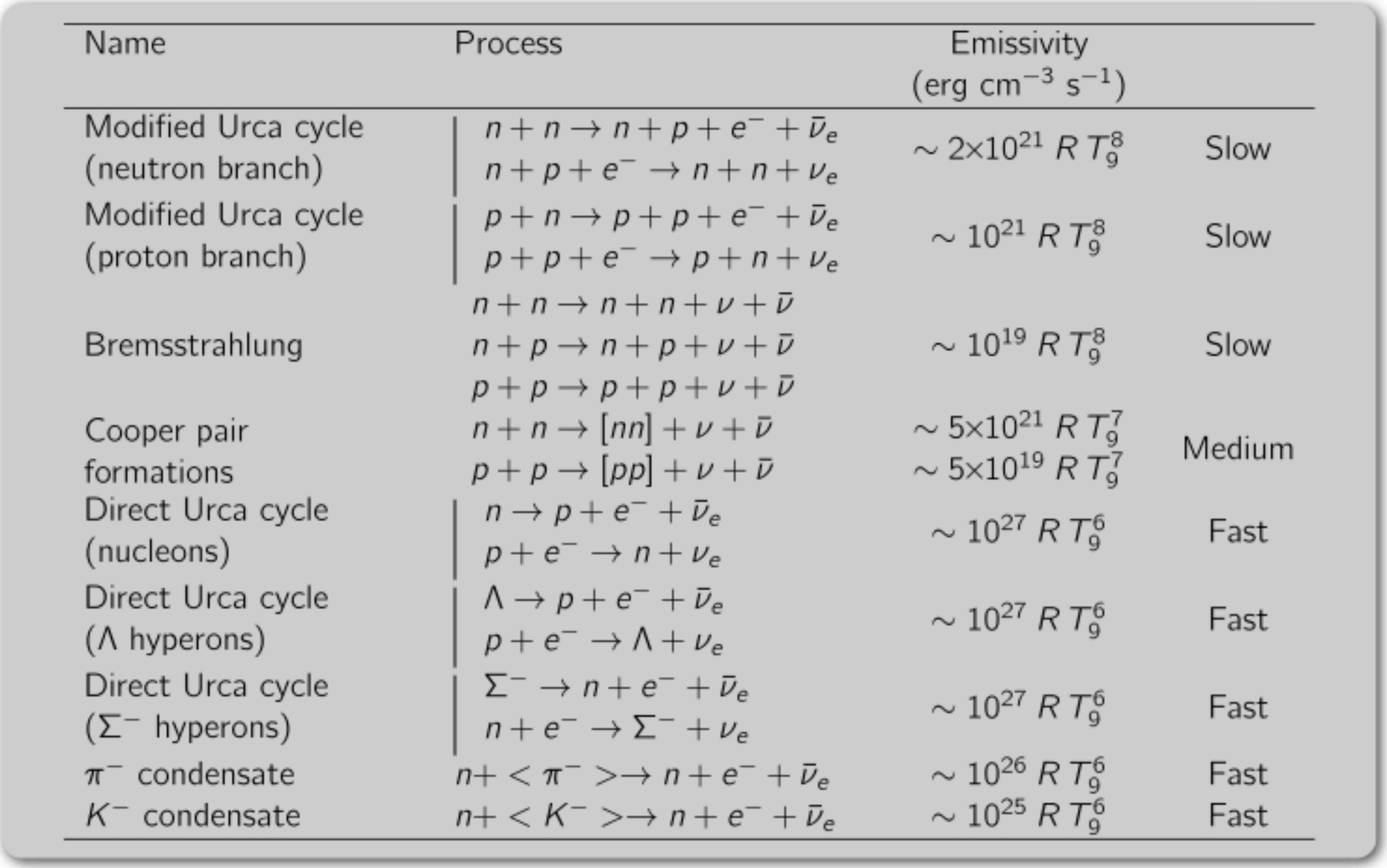


Surface photon emission
dominates at t > 10^6 yrs

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

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

Neutrino Emission



Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n + n \to n + p + e^- + \bar{\nu}_e$ $n + p + e^- \to n + n + \nu_e$	$\sim 2\times10^{21}\, R\, T_9^8$	Slow
Modified Urca cycle (proton branch)	$p + n \to p + p + e^- + \bar{\nu}_e$ $p + p + e^- \to p + n + \nu_e$	$\sim 10^{21}\, R\, T_9^8$	Slow
Bremsstrahlung	$n + n \to n + n + \nu + \bar{\nu}$ $n + p \to n + p + \nu + \bar{\nu}$ $p + p \to p + p + \nu + \bar{\nu}$	$\sim 10^{19}\, R\, T_9^8$	Slow
Cooper pair formations	$n + n \to [nn] + \nu + \bar{\nu}$ $p + p \to [pp] + \nu + \bar{\nu}$	$\sim 5\times10^{21}\, R\, T_9^7$ $\sim 5\times10^{19}\, R\, T_9^7$	Medium
Direct Urca cycle (nucleons)	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Λ hyperons)	$\Lambda \to p + e^- + \bar{\nu}_e$ $p + e^- \to \Lambda + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Σ^- hyperons)	$\Sigma^- \to n + e^- + \bar{\nu}_e$ $n + e^- \to \Sigma^- + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
π^- condensate	$n + <\pi^-> \to n + e^- + \bar{\nu}_e$	$\sim 10^{26}\, R\, T_9^6$	Fast
K^- condensate	$n + <K^-> \to n + e^- + \bar{\nu}_e$	$\sim 10^{25}\, R\, T_9^6$	Fast

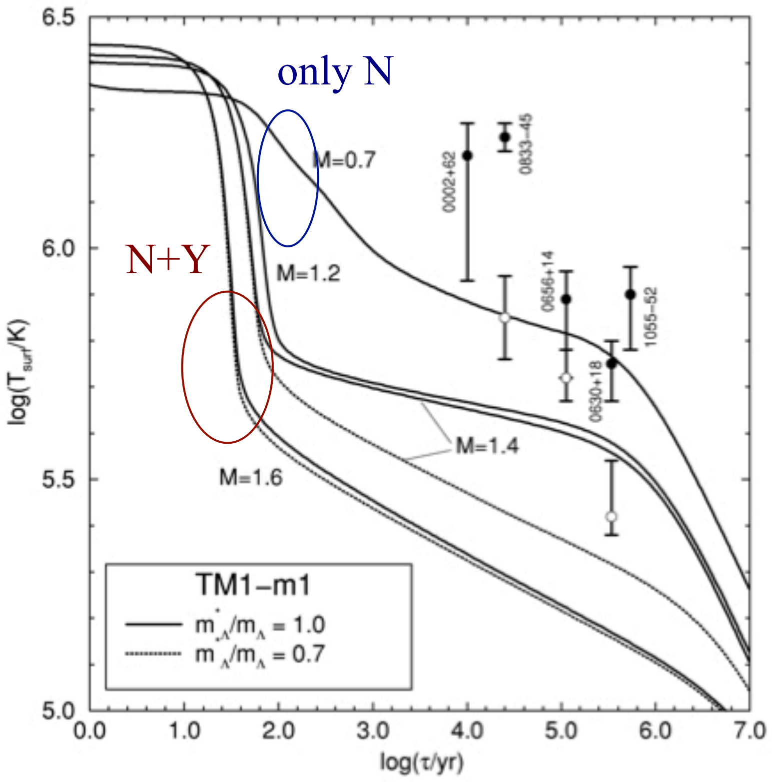
Anything beyond just neutrons & protons results in an enhancement of the neutrino emission

Hyperonic DURCA processes possible as soon as hyperons appear (nucleonic DURCA requires x_p > 11-15 %) → 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, …

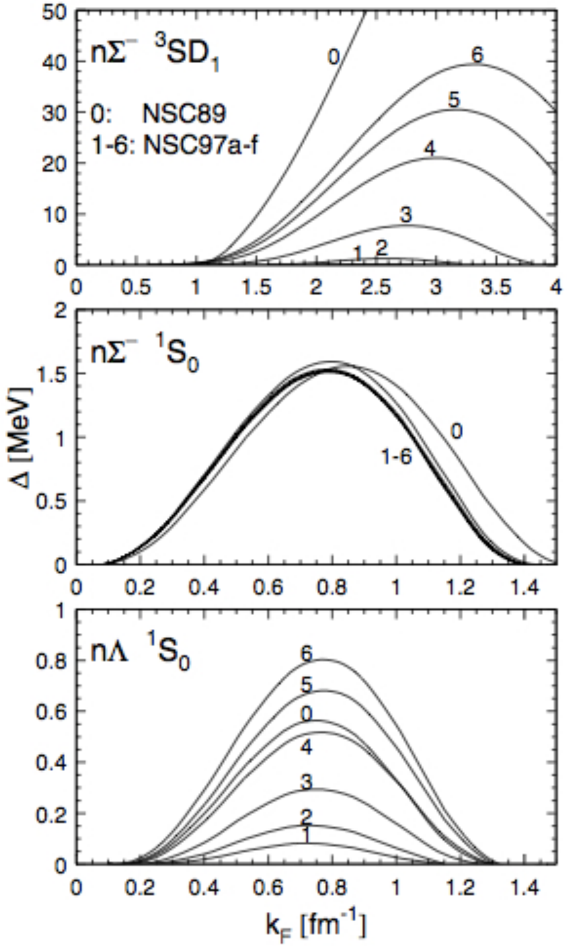
(Schaab, Shaffner-Bielich & Balberg 1998)



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

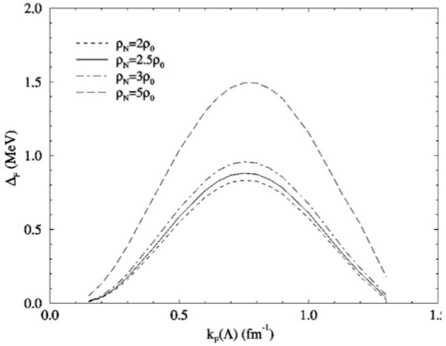
Pairing Gap ⟶ suppression of C_v & ε by $\sim e^{(-\Delta/k_BT)}$

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

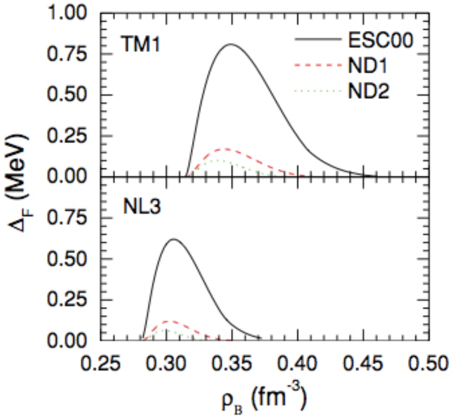


(Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0$ ΛΛ gap

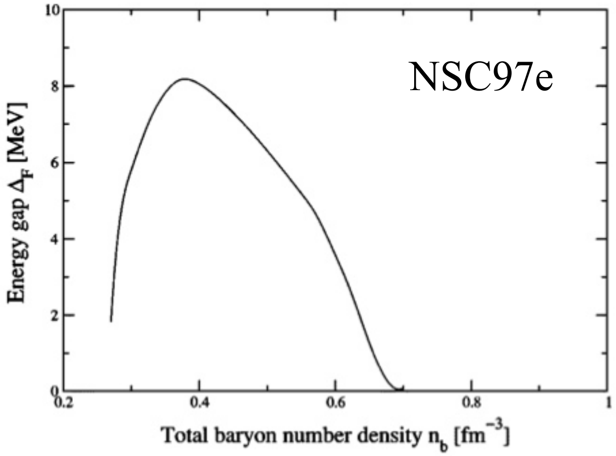


(Balberg & Barnea 1998)

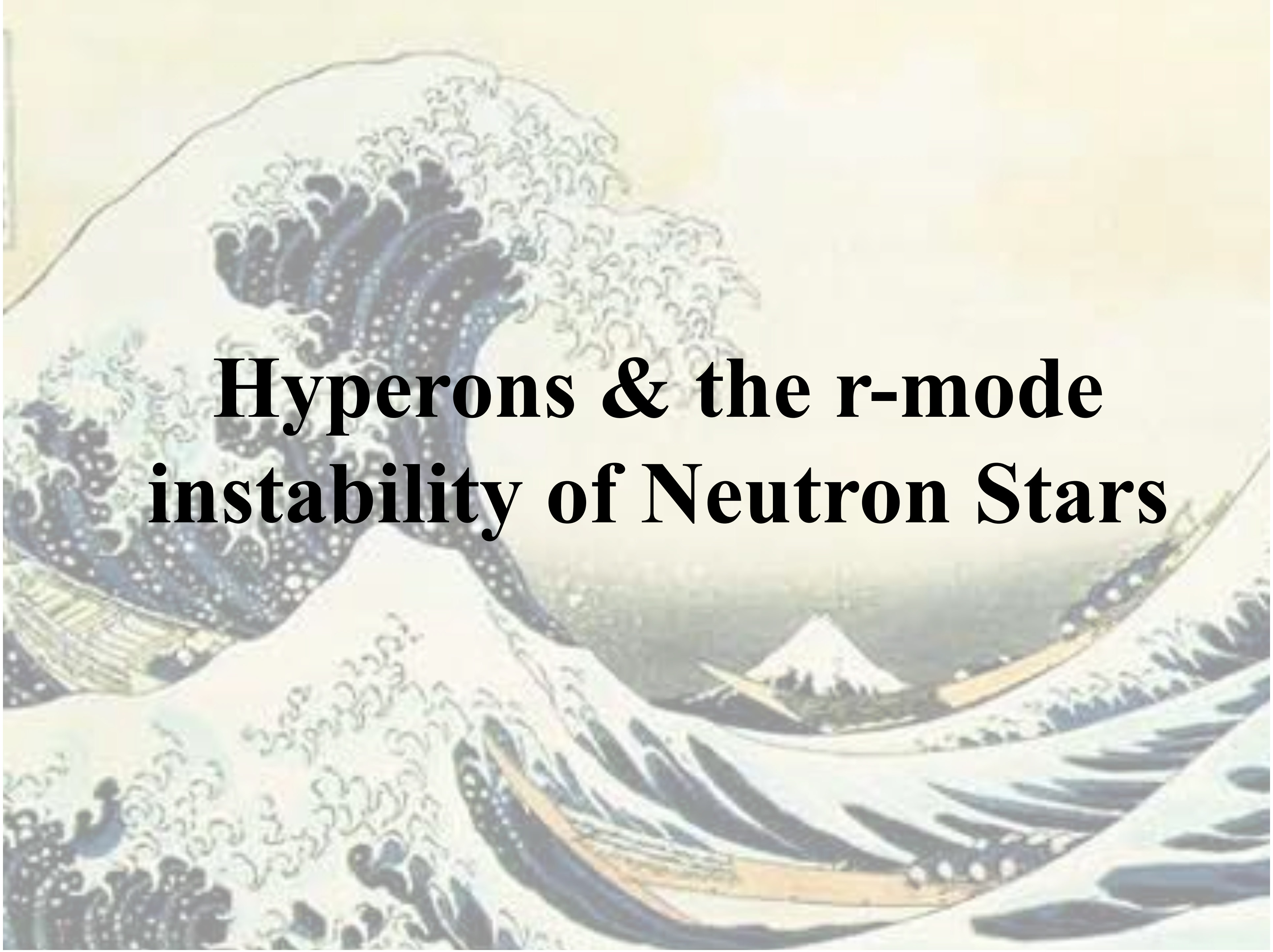


(Wang & Shen 2010)

- $^1S_0$ ΣΣ gap



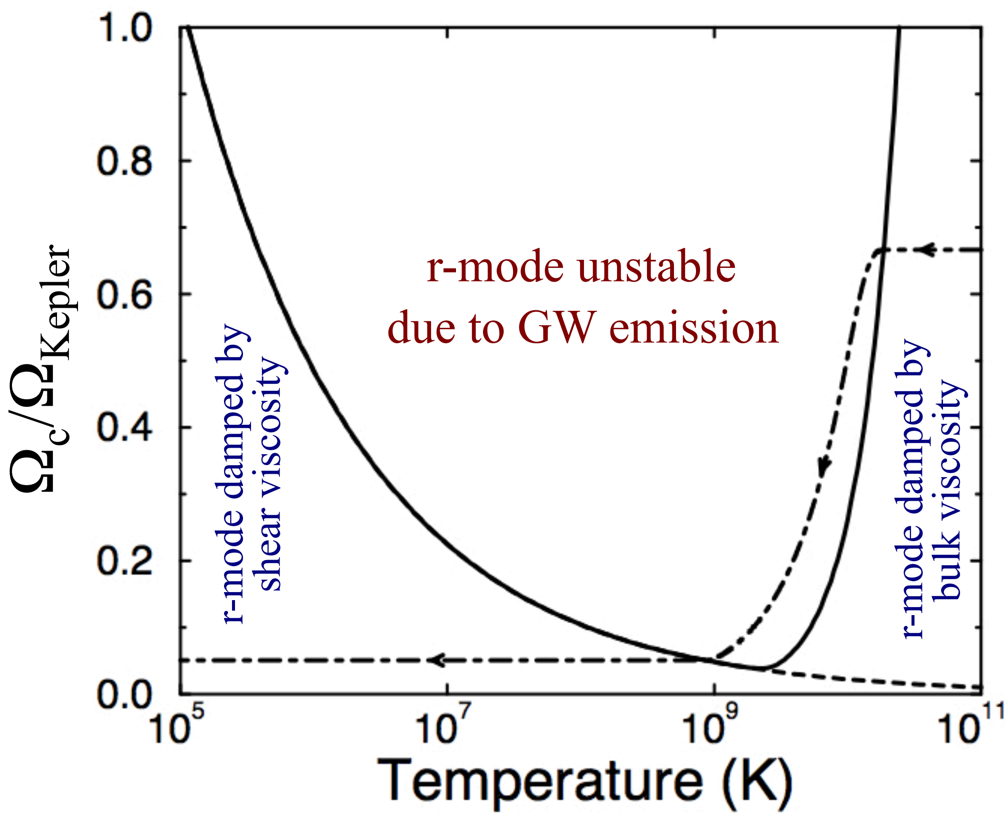
(I.V. & Tolós 2004)



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 (CFS mechanism)
  - GW makes the mode unstable
  - Viscosity stabilizes the mode

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

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

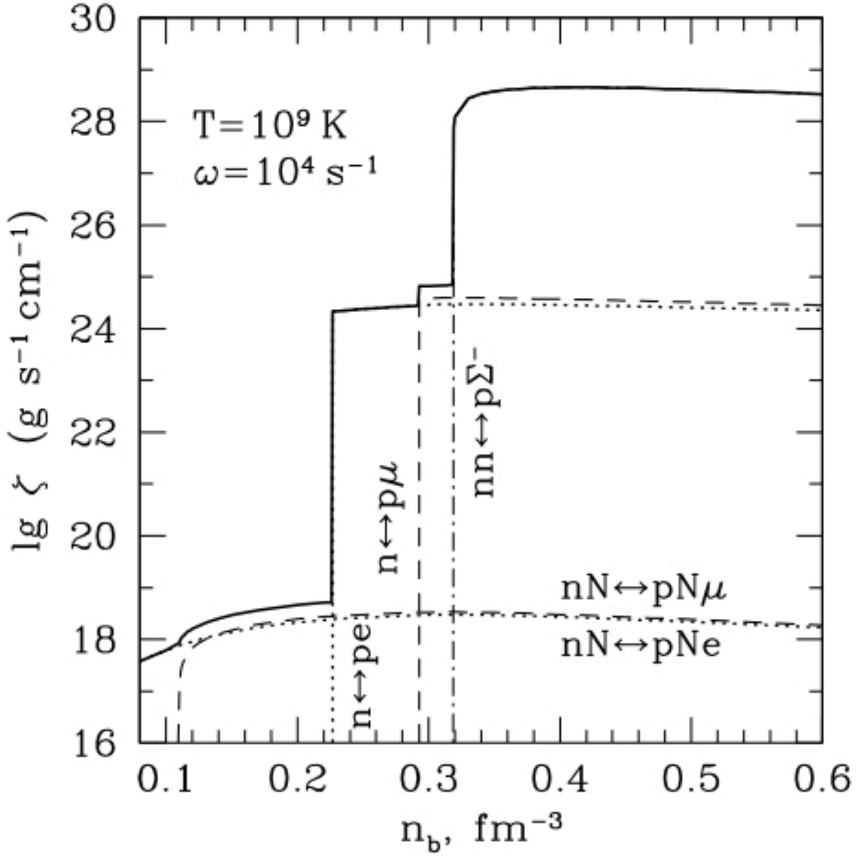
Hyperon Bulk Viscosity ξ_Y

(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 but (again) hyperon pairing gaps are poorly known

Critical Angular Velocity of Neutron Stars

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

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

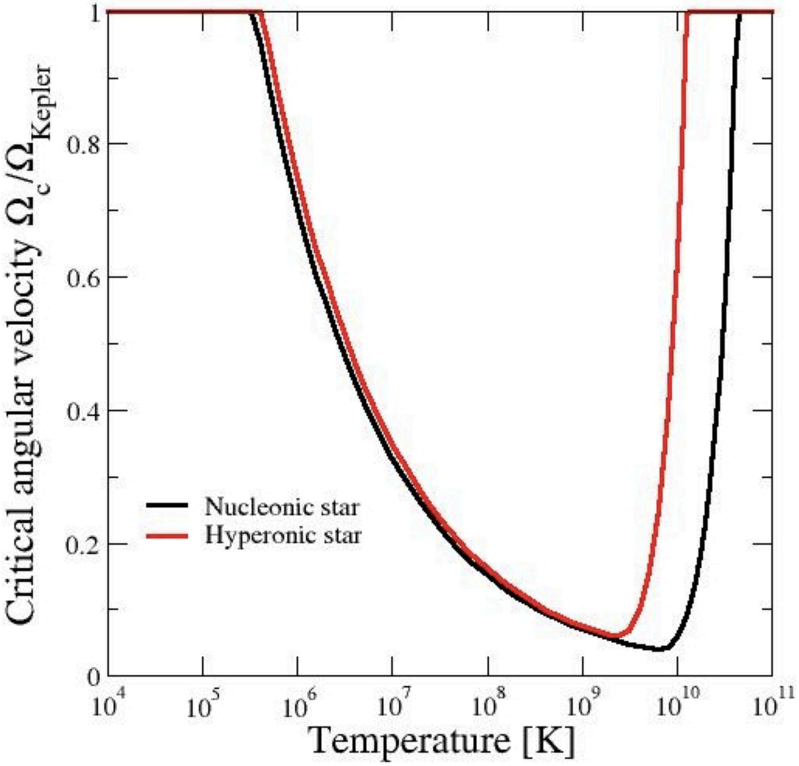
➔ $\frac{1}{\tau(\Omega_c,T)} = 0$ r-mode instability region

$\Omega < \Omega_c$ 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$M_{\odot}$)

The final message of this talk

Hyperons in Neutron Stars

✓ Strong softening of EoS & reduction of NS Mass

➔ Hyperons & Massive NS still an open question

✓ Additional Fast Cooling Processes

✓ Reduction of r-mode instability region

But hyperon pairing gaps are poorly known !!


Congratulations Xavier