Hyperons: the strange ingredients of the Neutron Star Equation of State

Isaac Vidaña, INFN Catania

JENAA Workshop on Nuclear Physics at the LHC & connections with Astrophysics
CERN, August 19th-20th 2024

In this talk …

First I will review some of the effects of hyperons on the properties of neutron stars, particularly, on

- ✧ EoS & maximum mass ("hyperon puzzle" & its possible solutions)
- ✧ Transport coefficients (thermal conductivity, shear viscosity)
- ✧ Cooling & r-mode instability

In the second part I will summarize some of the experimental constraints of YN & YY interactions, main ingredients to understand the role of hyperons in NSs

For details see:

I.V., Proc. R. Soc. A **474**: 20180145

Hyperons in Neutron Stars

The presence of hyperons in NS have been considered by many authors since the pioneering work of Ambartsumyan & Saakyan (1960)

Phenomenological approaches

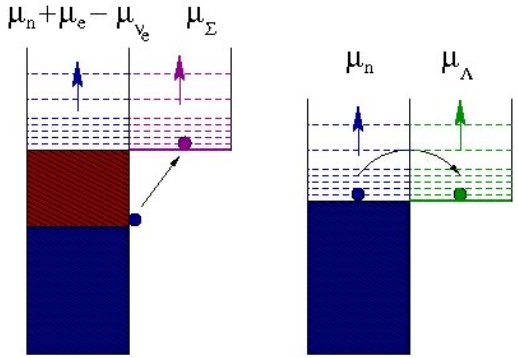
- Relativistic Mean Field Models: Glendenning 1985; Knorren et al. 1995; Shaffner-Bielich & Mishustin 1996, Bonano & Sedrakian 2012, …
- Non-relativistic potential model: Balberg & Gal 1997
- Quark-meson coupling model: Pal et al. 1999, …
- Chiral Effective Lagrangians: Hanauske et al., 2000
- Density 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, Logoteta, I.V. & Bombaci 2019
- DBHF: Sammarruca (2009), Katayama & Saito (2014)
- $V_{\text{low k}}$: Djapo, Schaefer & Wambach, 2010
- Quantum Monte Carlo: Lonardoni et al., (2014)

The Hyperon Puzzle: Still An Open Problem ?

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

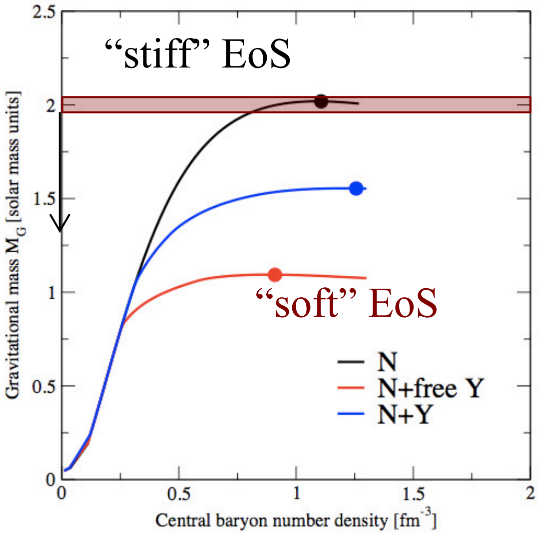


But

The relieve of Fermi pressure due to its appearance leads to a softer EoS and, therefore, to a reduction of the mass to values incompatible with recent observations

Observation of $\sim 2\,M_\odot$ NS → Any reliable EoS of dense matter should predict $M_{max}[EoS] > 2M_\odot$

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



Possible Solutions to the Hyperon Puzzle

The solution requires a mechanism that could eventually provide the additional pressure at high densities needed to make the EoS stiffer and, therefore, M_{max} compatible with current observational limits. Possible mechanisms could come from:

- Two-body YN & YY interactions
  - YY vector meson repulsion: ϕ meson coupled only to hyperons yielding strong repulsion at high ρ
  - Chiral forces: YN from χEFT predicts Λ s.p. potential more repulsive than those from meson exchange
- Hyperonic Three Body Forces

  Natural solution based on the known importance of 3N forces in nuclear physics
- Quark Matter Core

  Phase transition to deconfined QM at densities lower than hyperon threshold

Eur. Phys. J. A (2019) **55**: 207
DOI 10.1140/epja/i2019-12909-9

THE EUROPEAN PHYSICAL JOURNAL A

Letter

Impact of chiral hyperonic three-body forces on neutron stars

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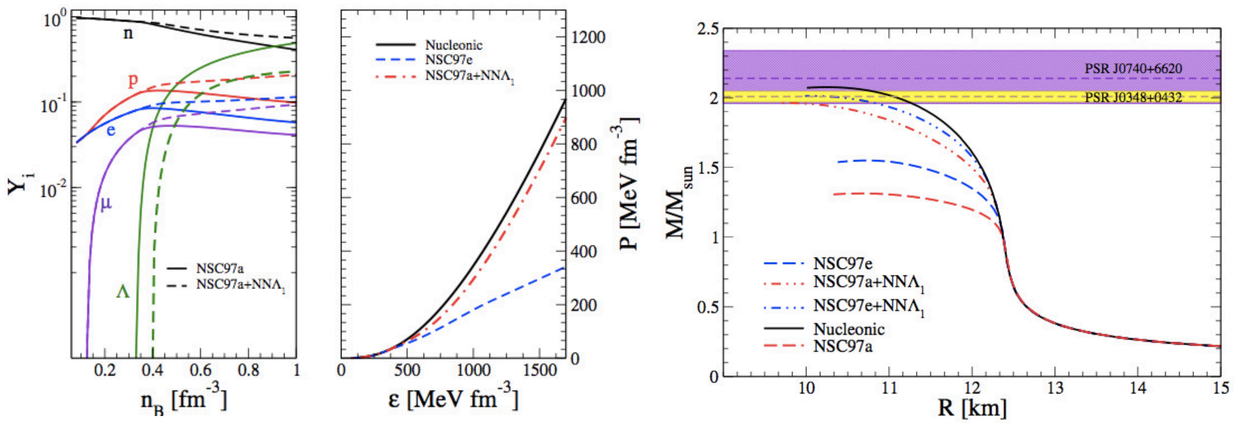
Received: 24 September 2019
Published online: 15 November 2019

Communicated by F. Gulminelli

Abstract. We study the effects of the nucleon-nucleon-lambda (NNΛ) three-body force on neutron stars. In particular, we consider the NNΛ force recently derived by the Jülich-Bonn-Munich group within the framework of chiral effective field theory at next-to-next-to-leading order. This force, together with realistic nucleon-nucleon, nucleon-nucleon-nucleon and nucleon-hyperon interactions, is used to calculate the equation of state and the structure of neutron stars within the many-body non-relativistic Brueckner-Hartree-Fock approach. Our results show that the inclusion of the NNΛ force leads to an equation of state stiff enough such that the resulting neutron star maximum mass is compatible with the largest currently measured ($\sim 2\,M_\odot$) neutron star masses. Using a perturbative many-body approach we calculate also the separation energy of the Λ in some hypernuclei finding that the agreement with the experimental data improves for the heavier ones when the effect of the NNΛ force is taken into account.

EPJ A Highlight - Towards the solution of the "hyperon puzzle"

"Even if the comparison with the observation still shows some tension, this is the first work showing without any ad-hoc adjustment of phenomenological parameters that the presence of hyperons in the core can be compatible with hyper-massive neutron star"



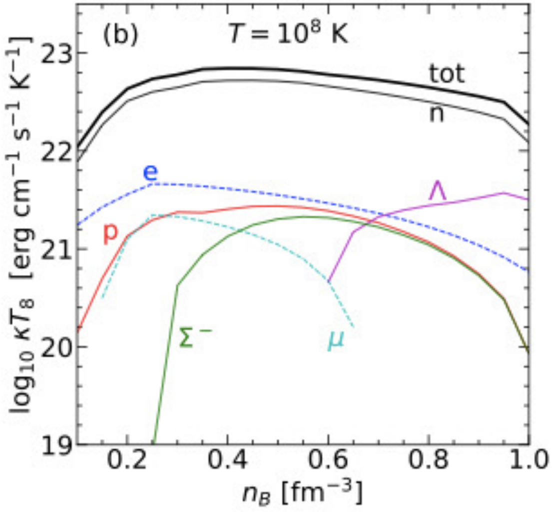
- NS matter described as a mixture of n, p, e$^-$, μ$^-$ & Λ's in β-equilibrium
- χEFT (NN, NNN, NNΛ) + meson-exchange (NY)
- Even if the concentration of Λ's is strongly reduced they are still present in the interior of a 2M$_\odot$ NS
- Moderate NNΛ repulsion (~ 10 MeV at saturation)

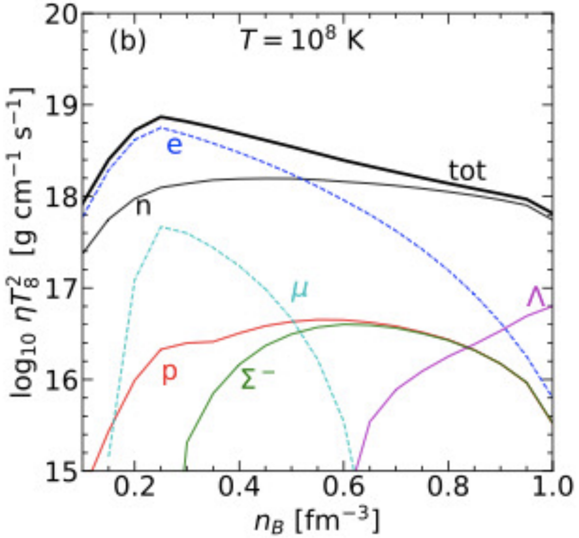
Λ separation energies of the s-wave state (not adjusted)

	$^{41}_{\Lambda}$Ca	$^{91}_{\Lambda}$Zr	$^{209}_{\Lambda}$Pb
NSC97a	23.0	31.3	38.8
NSC97a+NNΛ_1	14.9	21.1	26.8
NSC97a+NNΛ_2	13.3	19.3	24.7
NSC97e	24.2	32.3	39.5
NSC97e+NNΛ_1	16.1	22.3	27.9
NSC97e+NNΛ_2	14.7	20.7	26.1
Exp.	18.7(1.1)†	23.6(5)	26.9(8)

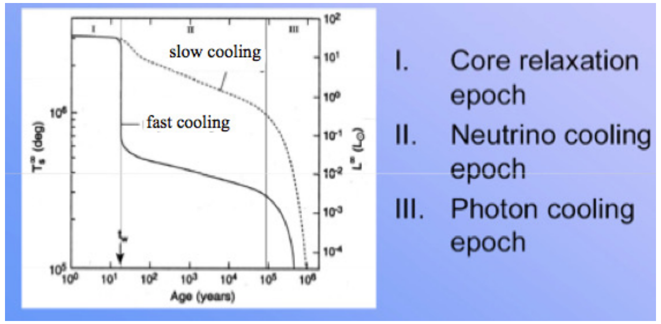
Transport coefficients of hyperonic neutron star cores

Most of the effort have been concentrated on the role of hyperons in the EoS of NSs. However, NSs are **evolving objects** where various **dynamical processes** can occur. Their theoretical description requires **in addition to the EoS** the **knowledge of transport properties (*e.g.*, thermal conductivity, shear viscosity) of dense NS matter** needed to understand NS cooling mechanism and/or their oscillation modes



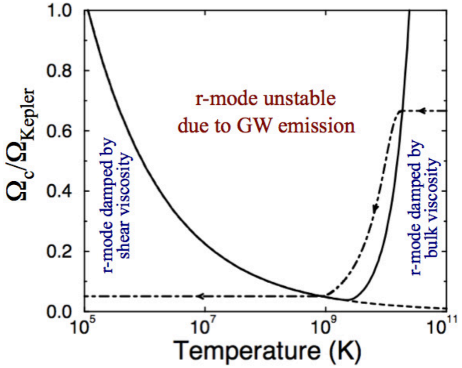


Cooling



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

r-mode instability window



$$\frac{1}{\tau(\Omega,T)} = -\frac{1}{\tau_{GW}(\Omega)} + \frac{1}{\tau_{Viscosity}(\Omega,T)} = 0$$

Recent calculation of thermal conductivity, shear viscosity of non-superfluid npΣΛeμ based on theory of multicomponent Fermi liquids using as microscopic inputs (in-medium scattering matrices, NS composition & effective masses)

Shternin & Vidaña, Universe 7, 203 (2021)

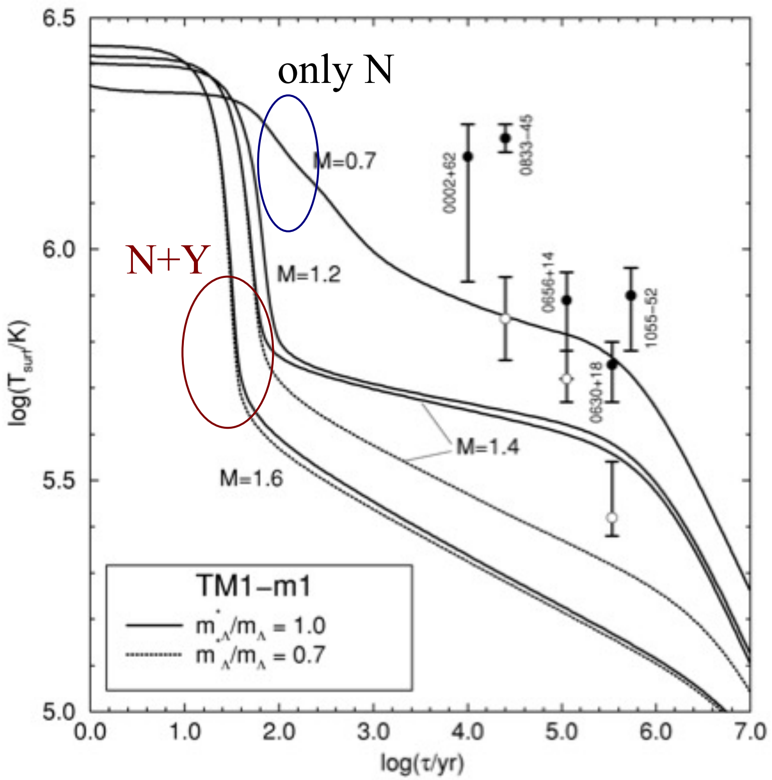
Hyperons & NS cooling

Hyperonic direct URCA processes are possible as soon as hyperons appear leading to additional fast cooling mechanisms

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 emissivity w.r.t. nucleonic DURCA

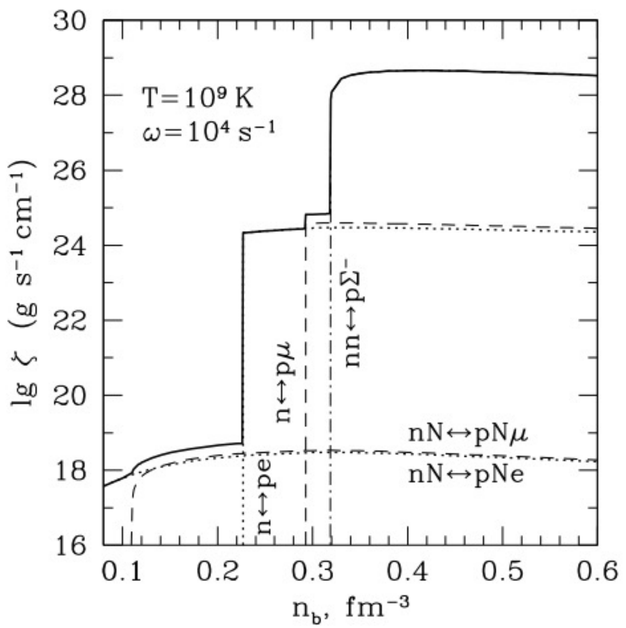
The r-mode instability: Hyperon Bulk Viscosity ξ_Y

(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,…)

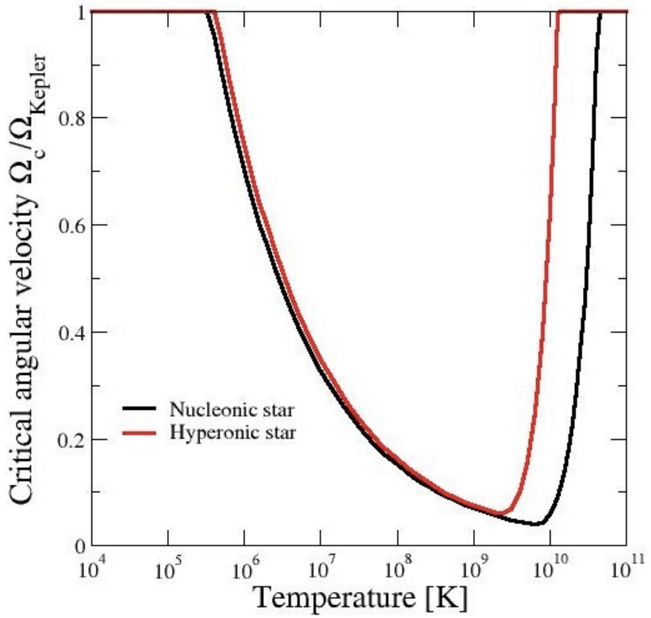
Sources of ξ_Y:

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)



(Vidaña & Albertus in preparation)



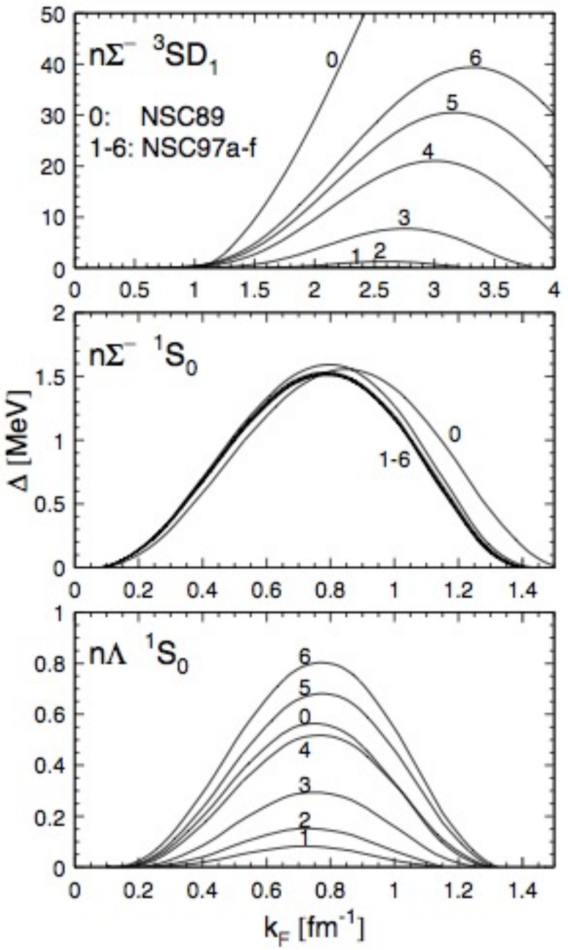
Reaction Rates & ξ_Y reduced by Hyperon Superfluidity

As expected:

smaller r-mode instability regiondue to hyperons which introduce additional sources of viscosity

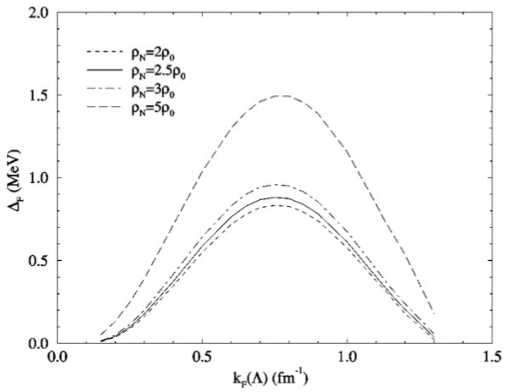
Pairing gaps are important for cooling calculations since they reduce specific heat & emissivities by an exponential factor $exp\left(-\Delta/_{k_B T}\right)$

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

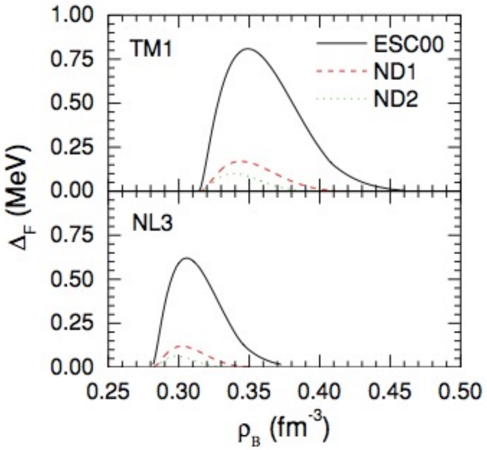


(Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0$ ΛΛ gap

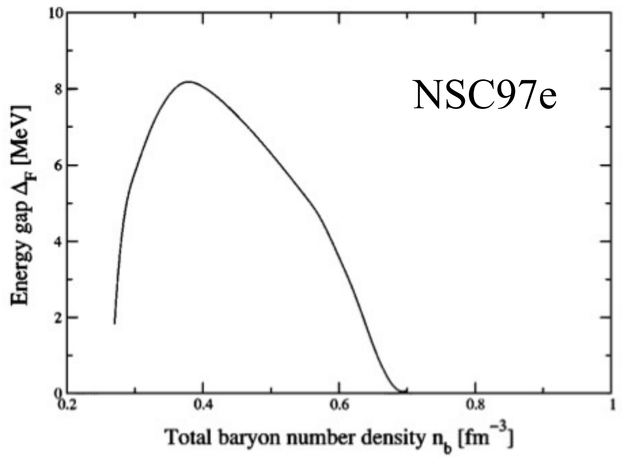


(Balberg & Barnea 1998)



(Wang & Shen 2010)

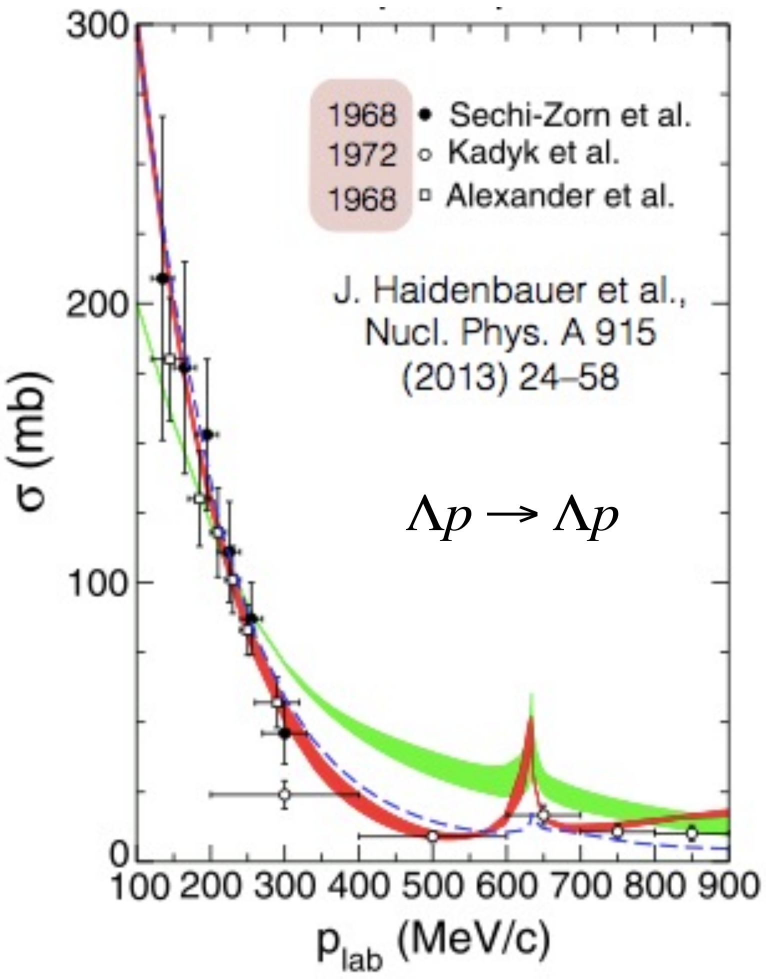
- $^1S_0$ ΣΣ gap



(Vidaña 2004)

The main ingredients to understand the role of hyperons in NSs are the YN &YY interactions. But how much do we know to constrain them ?

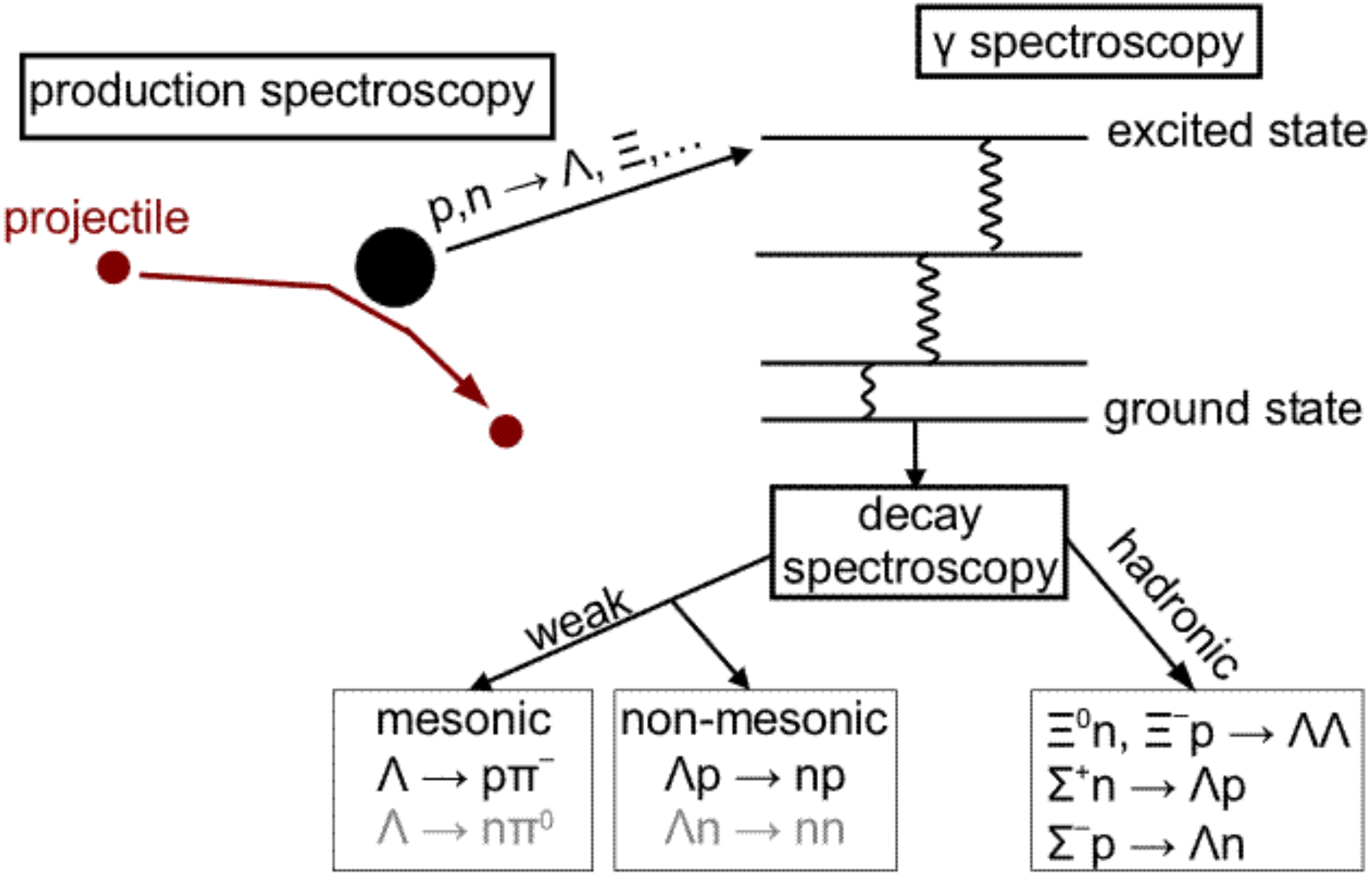
Unfortunately, much less than in the pure nucleonic sector



- 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)

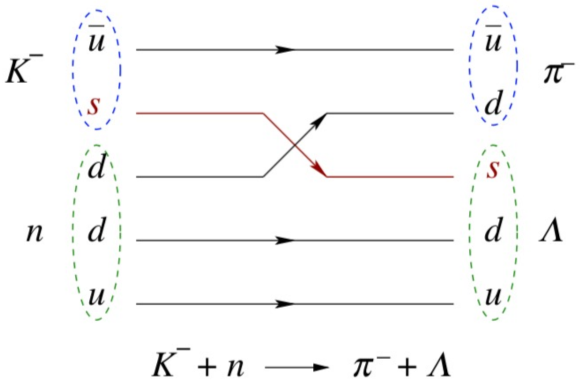
Alternative and complementary information can be obtained from the study of hypernuclei with the goal of relating hypernuclear observables with the underlying bare YN & YY interactions



Production of single-Λ hypernuclei

✧ Strangeness exchange (BNL, KEK, JPARC)

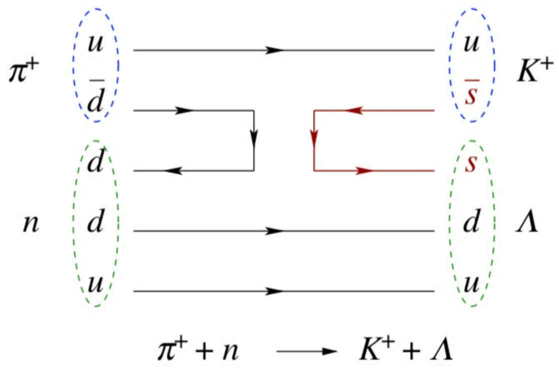
$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$



(replace an u or d quark by an s one)

✧ Associate production (BNL, KEK, GSI)

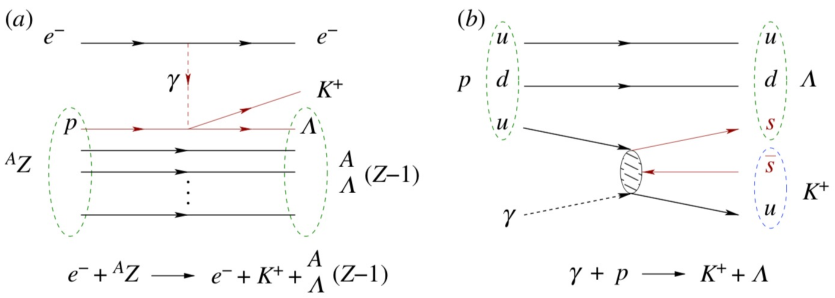
$$\pi^+ + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^+$$



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

✧ Electroproduction (JLAB, MAMI-C)

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



✧ Hypernuclei production in relativistic heavy ion collisions (HypHII collaboration FAIR/GSI)

First experiment with ^{6}Li beam on ^{12}C target at 2GeV. Λ, $^{3}_{\Lambda}$H & $^{4}_{\Lambda}$H observed.

Production of double-Λ hypernuclei

Best systems to investigate the properties of $S = -2$ baryon–baryon interaction

Contrary to single-Λ hypernuclei they are produced in a two-step process

- Ξ^- production in process like
  - ✓ (K^-,K^+) reaction (BNL, KEK)

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

  - ✓ Antiproton production (PANDA@FAIR)

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

- Ξ^- captured in an atomic orbit interacts with the nuclear core producing two Λ's

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

Binding energy $\Delta B_{\Lambda\Lambda}$ of two Λs in double-Λ hypernuclei

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

Earlier emulsion experiments reported the formation of ${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be & ${}^{13}_{\Lambda\Lambda}$B but the identification of the last two was ambiguous. The value of the Nagara event recently revised $\Delta B_{\Lambda\Lambda}$=0.67$\pm$0.17 MeV due to a change of the Ξ^-mass

	$B_{\Lambda\Lambda}$ (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

Production of single-Σ and single-Ξ hypernuclei

- ✓ Production of single-Σ hypernuclei mechanisms similar to the ones considered for Λ hypernuclei like, e.g., strangeness exchange (K^-,$\pi^\pm$). However, their existence has not been experimentally confirmed yet without ambiguity, suggesting that the Σ nucleon interaction is most probably repulsive.

- ✓ Single-Ξ hypernuclei can be produced by means of (K^-, K^+) reactions & antroproton production

  - A first analysis [1] of $^{12}\mathrm{C}(K^-,K^+)^{12}_{\Xi^-}\mathrm{Be}$ reaction indicated an attractive Ξ-nucleus interaction of the order of about -14 MeV, but an independent analysis [2] of the $(K^-,K^+)\Xi$ production spectrum on $^{12}\mathrm{C}$ found instead an almost zero Ξ-nucleus potential

  - A deeply bound state of the $\Xi^- - {}^{14}\mathrm{N}$ system with a binding energy of 4.38 ± 0.25 MeV has been observed [3]. Future Ξ-hypernuclei production experiments are being planned at JPARC

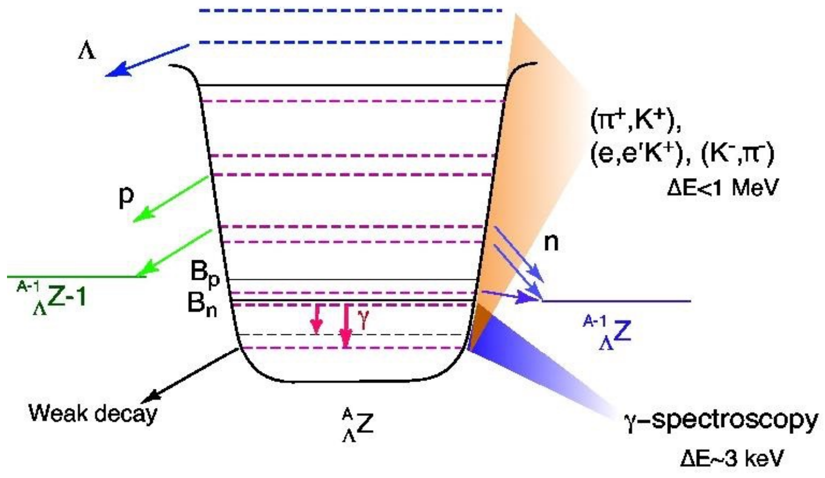
[1] Khaustov et al. PRC 61, 054603 (2000)

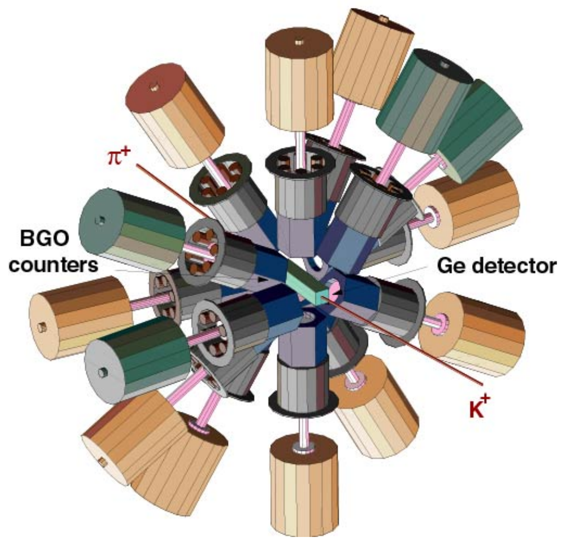
[2] Kohno et al. PTP 123, 157 (2010); NPA 835, 358 (2010)

[3] Nakazawa et al. PTEP 033D02 (2015)

Hypernuclear γ-ray spectroscopy

- ✧ Produced hypernuclei can be in an excited state
- ✧ Energy released by emission of neutrons or protons or sometimes by γ-ray when the hyperon moves to lower states.

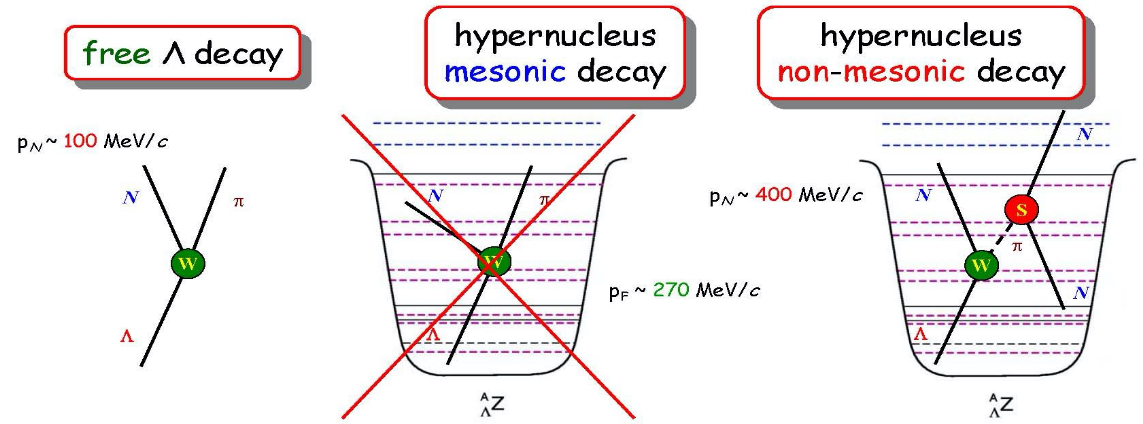




Large acceptance Germanium detector
(Hyperball at BNL)

- ✧ The detection of γ-ray transitions with with Ge (NaI) detectors has allowed the analysis of hypernuclear excited states with excellent resolution. Some weaks points still exists:
  - ➢ Λ depth potential in nucleus ~ 30 MeV ➔ observation of γ~rays limited to low excitation region
  - ➢ γ~ray transition measures only energy difference between two states. Measurement of two γ rays in coincidence might help to resolve it

The Weak Decay of Λ hypernuclei

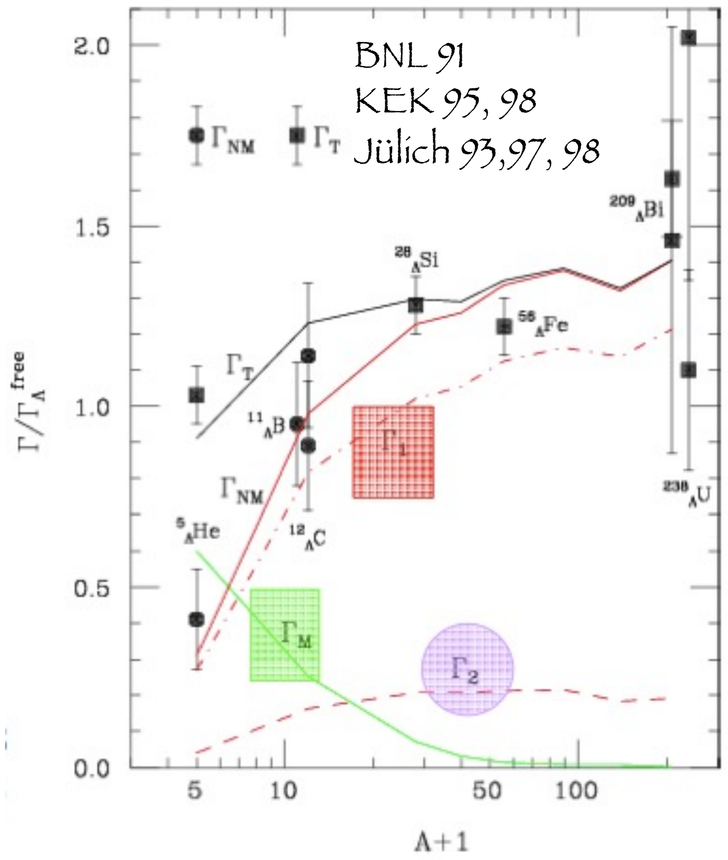


$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)
$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)
$\tau_\Lambda = 263$ ps

suppressed by Pauli blocking

$\Lambda + n \rightarrow n + n + 176$ MeV
$\Lambda + p \rightarrow n + p + 176$ MeV

$$\Gamma \sim \Gamma_\Lambda^{free} = 3.8 \times 10^9\, s^{-1}$$



W. M. Alberico et al., Phys. Rev. C 61, 044314 (2000)

(well reproduced by theoretical models)

$$\Gamma = \Gamma_M + \Gamma_{NM} + \Gamma_{2N} = \Gamma_{\pi^0} + \Gamma_{\pi^-} + \Gamma_n + \Gamma_p + \Gamma_{np}$$

$\Lambda \rightarrow N\pi$
$p_N \sim 100\, MeV$

$\Lambda N \rightarrow NN$
$p_N \sim 420\, MeV$

$\Lambda NN \rightarrow NNN$
$p_N \sim 340\ \ MeV$

But there are some 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., meson-exchange & chiral effective field theory models)

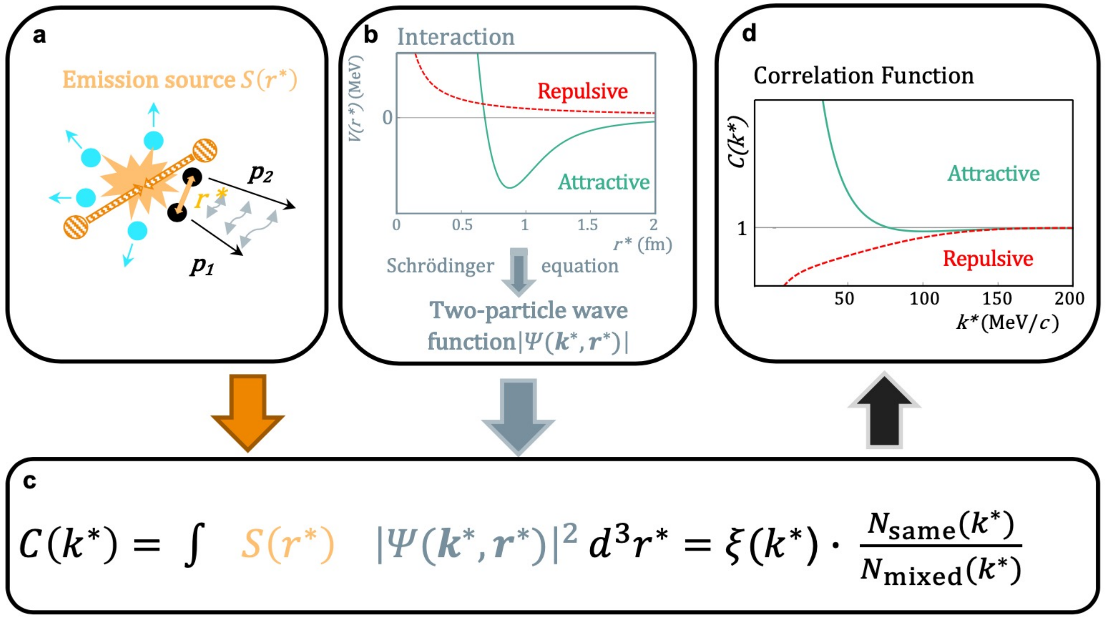
- ✧ Bare YN & YY is not easy to derive from hypernuclei. Hyperons in nuclei are not free but in-medium. Hypernuclei provide effective hyperon-nucleus interactions

- ✧ 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

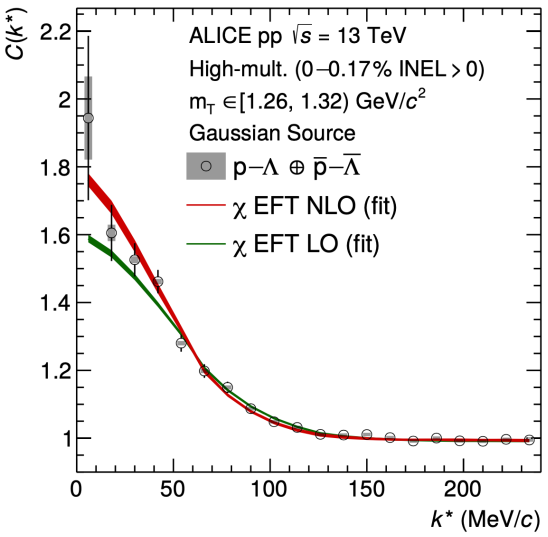
Constraints of YN, YY & YNN interactions from Femtoscopy

Information on the YN interaction, additional to that from scattering & hypernuclei, together with constraints on the YY one and YNN has begun to be recently available thanks the to **femtoscopy technique** by measuring the correlations of YN pairs and YNN triads in *p-p* and *p-Pb* collisions at LHC by the ALICE collaboration

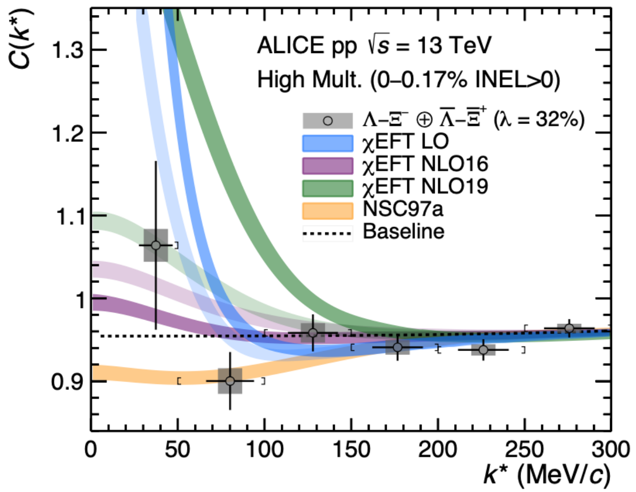


ALICE collaboration, Nature 588, 232 (2021)

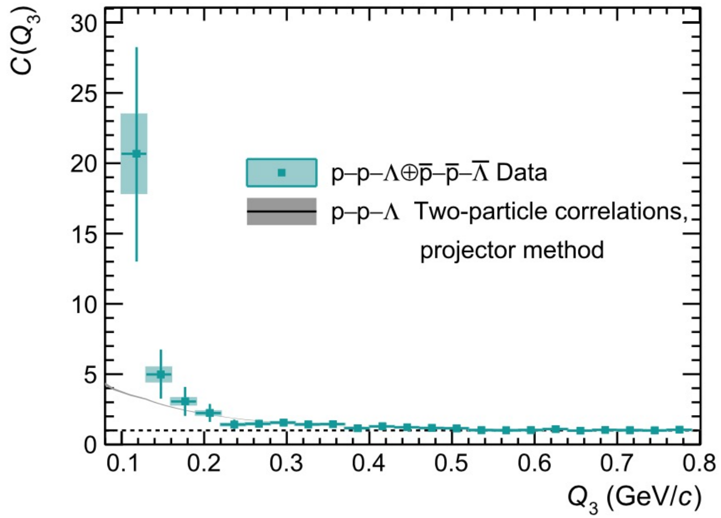
Acharya et al., PLB 811, 135849 (2020)



Acharya et al., PLB 844, 137223 (2022)



ALICE collaboration, EPJA 59, 145 (2023)



Very recently the NLO19 chiral model has been constrained from the combined analysis of pΛ cross section and pΛ CF

Phys. Lett. B 850 (2024) 138550

Contents lists available at ScienceDirect

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Letter

Constraining the pΛ interaction from a combined analysis of scattering data and correlation functions

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ARTICLE INFO

Editor: A. Schwenk

Keywords:
Scattering
Femtoscopy
Chiral effective field theory

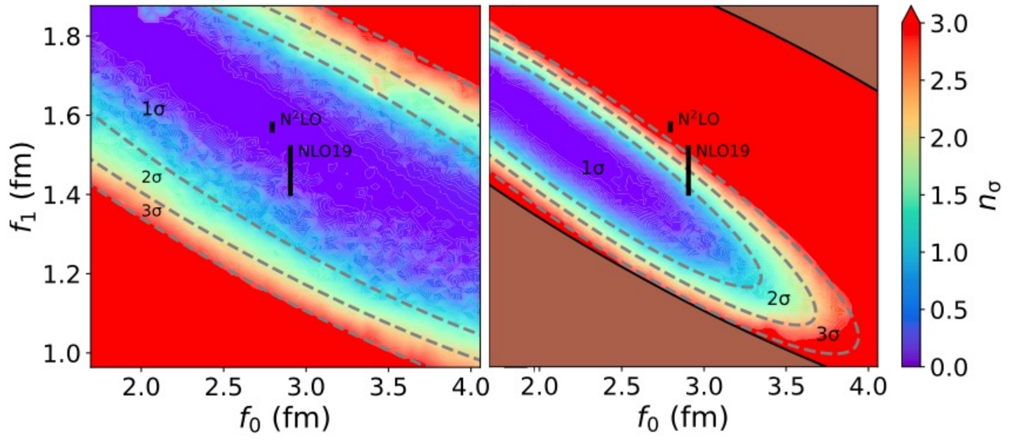
ABSTRACT

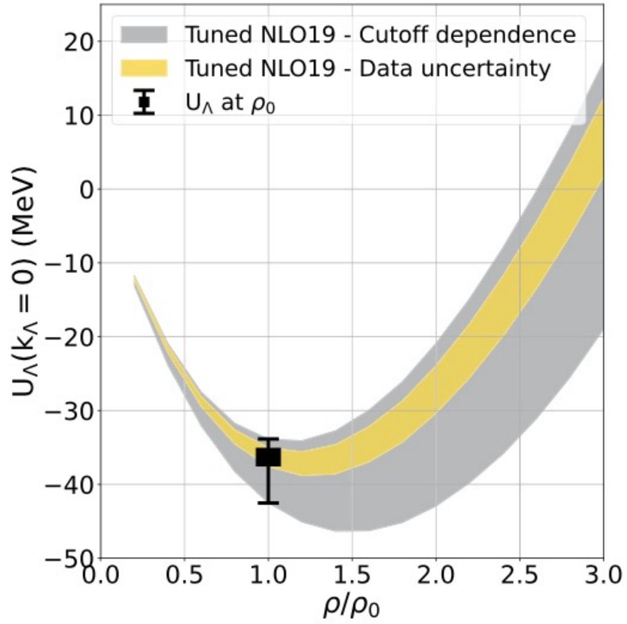
This work provides the first combined analysis of low-energy pΛ scattering, considering both cross section and correlation data. The obtained results establish the most stringent constraints to date on the two-body pΛ interaction, pointing to a weaker attraction than so far accepted. The best set of scattering lengths for the spin singlet and triplet are found to range from $f_0, f_1 = (2.1, 1.56)$ to $(3.34, 1.18)$ fm. With a chiral NY potential fine-tuned to those scattering parameters, the in-medium properties of the Λ are explored and a potential depth of $U_\Lambda = -36.3 \pm 1.3(\mathrm{stat})^{+2.5}_{-6.2}(\mathrm{syst})$ MeV is found at nuclear matter saturation density.

Usmani parameterization	f_0 (fm)	f_1 (fm)	$n\sigma_{\mathrm{fmt}}$	$n\sigma_{\mathrm{sct}}$	$n\sigma_{\mathrm{tot}}$
NLO13(600)	2.91	1.54	5.2	0.0	4.6
NLO19(600)	2.91	1.41	1.7	0.4	1.1
N^2LO(550)	2.79	1.58	5.4	0.0	4.8
i	2.10	1.44	0.2	2.1	1.0
ii	**2.10**	**1.56**	**0.0**	**0.9**	**0.0**
iii	2.10	1.66	1.8	0.2	1.0
iv	2.50	1.32	0.2	2.2	1.1
v	**2.50**	**1.46**	**0.2**	**0.8**	**0.0**
vi	2.50	1.55	1.8	0.2	1.0
vii	**2.91**	**1.32**	**0.1**	**1.5**	**0.3**
viii	3.34	1.18	1.2	0.9	1.0

pΛ cross section

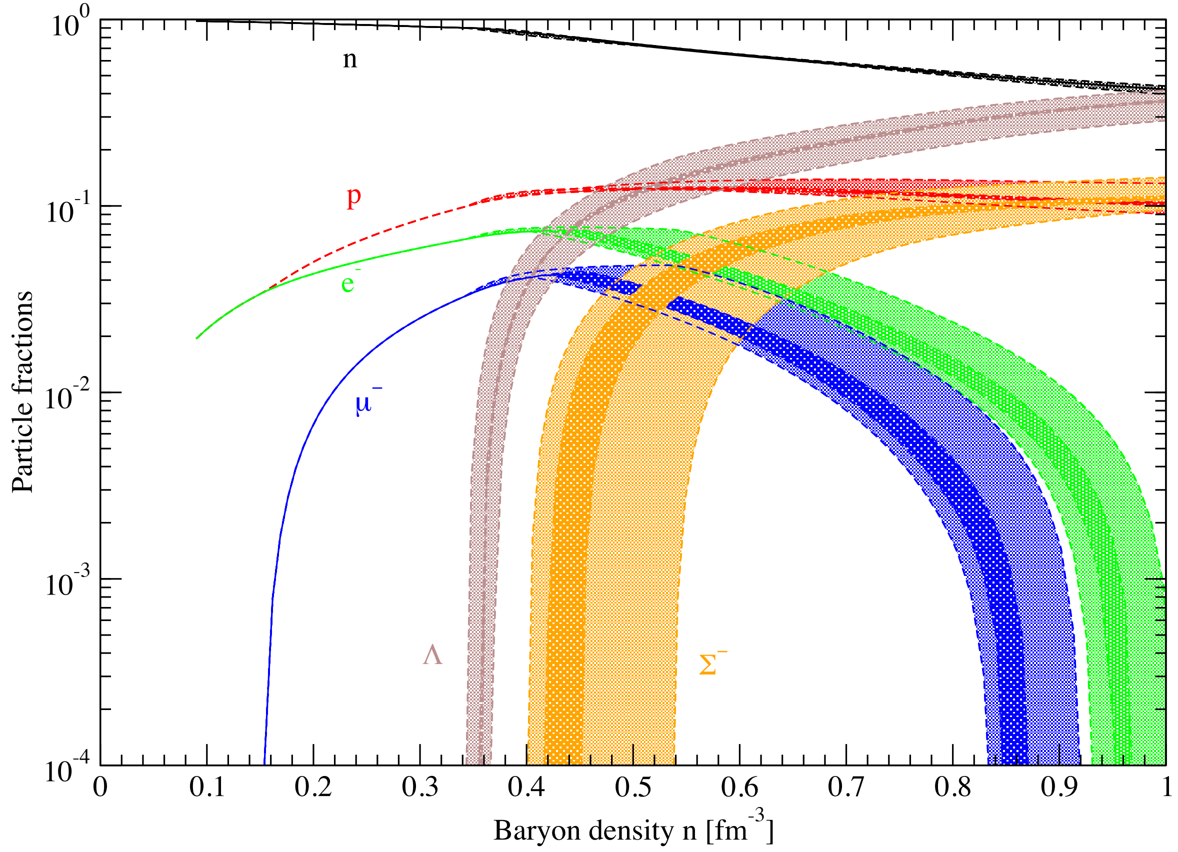
cross section+ pΛ CF



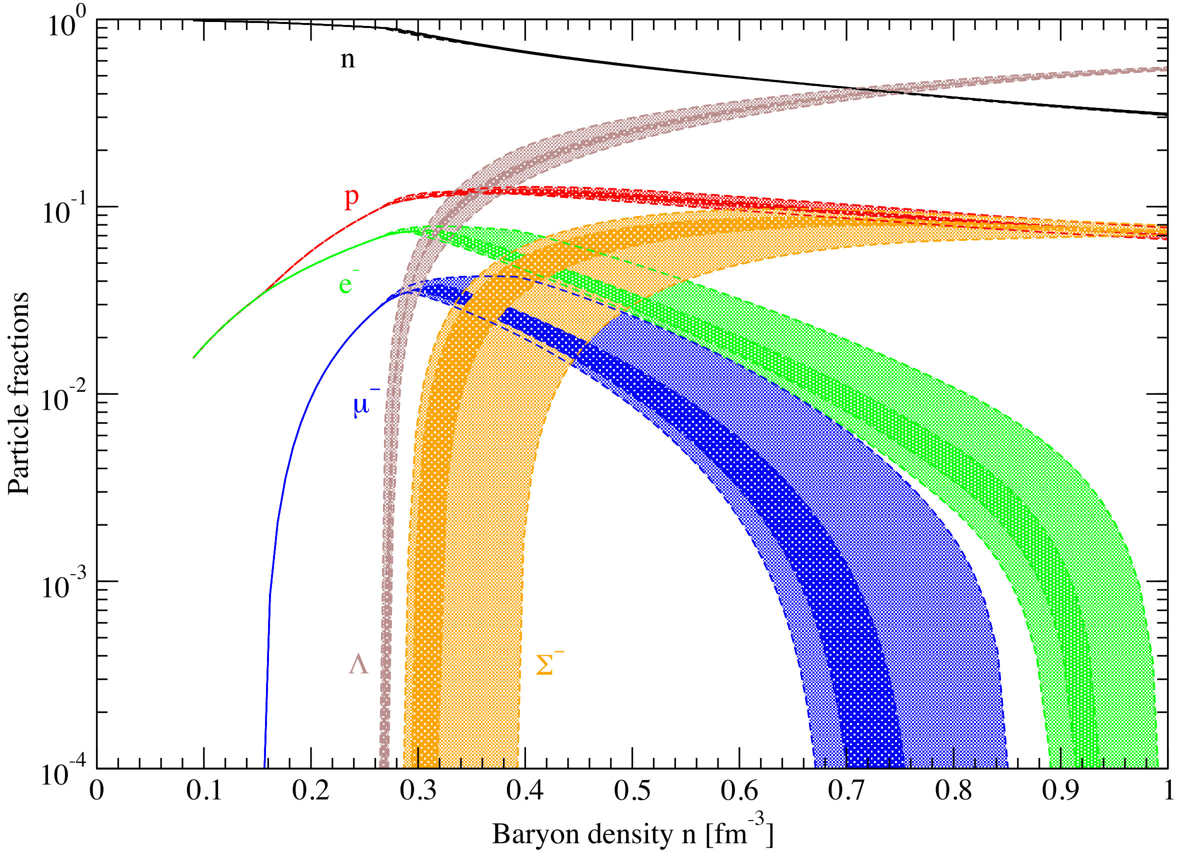


Composition of Neutron Star Matter

- NN (Av18)+ NNN1 (K=160 MeV)
- NY (Tuned NLO19 to femtoscopic data)



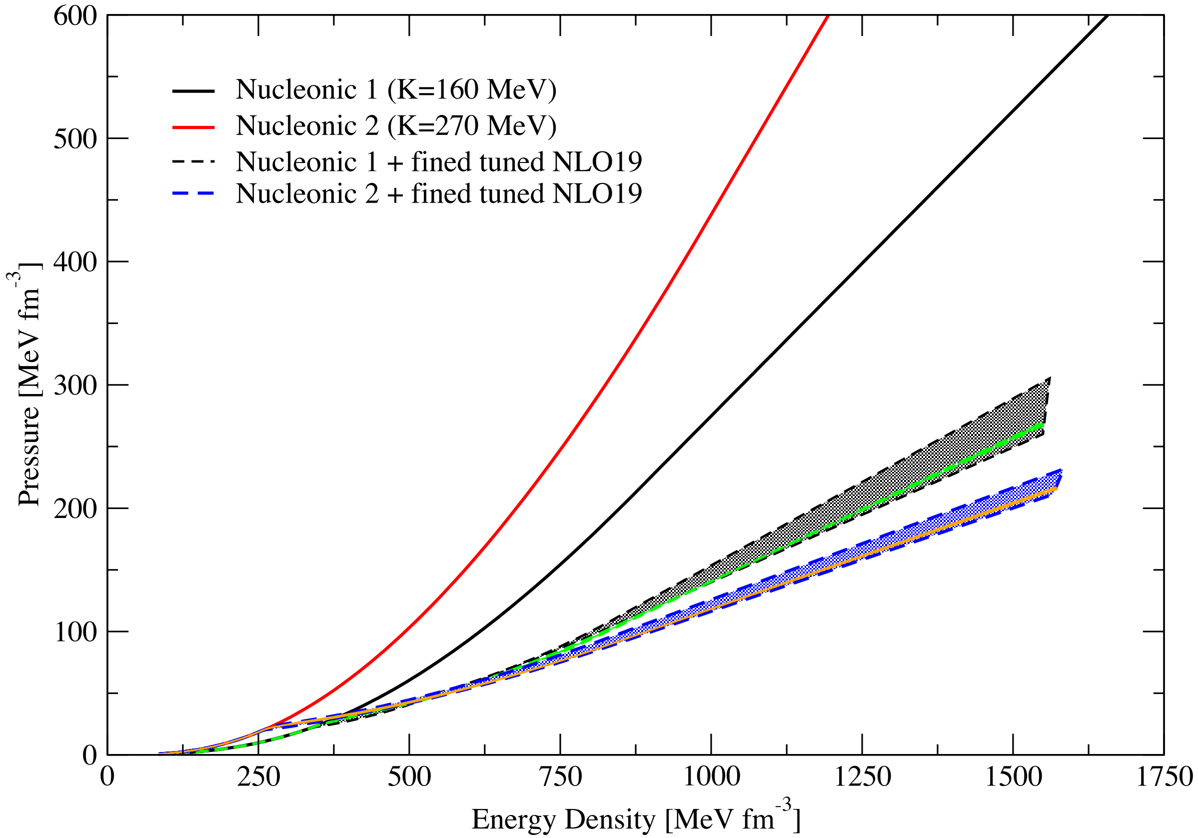
- NN (Av18)+ NNN2 (K=270 MeV)
- NY (Tuned NLO19 to femtoscopic data)

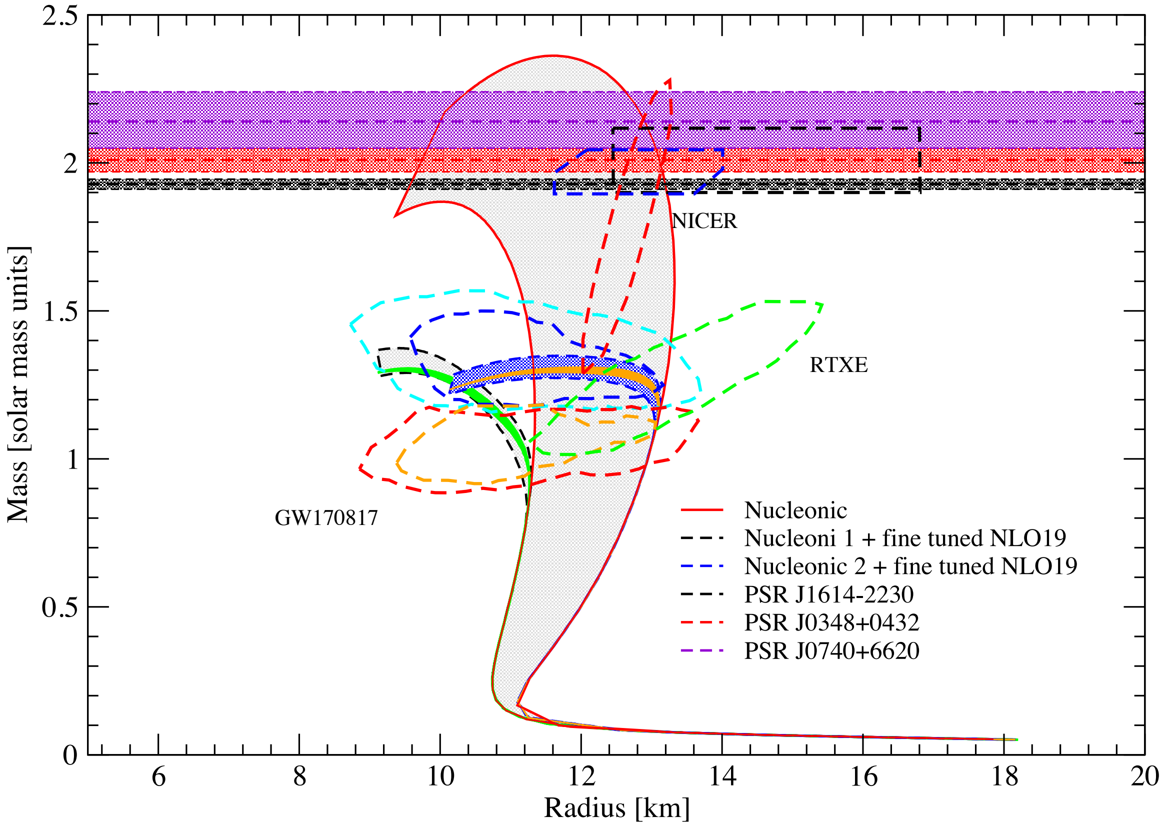


Large bands: residual cut-off uncertainty

Small bands: uncertainty from femtoscopic data (cut-off 600 MeV)

Neutron star EoS & Mass-Radius Relation

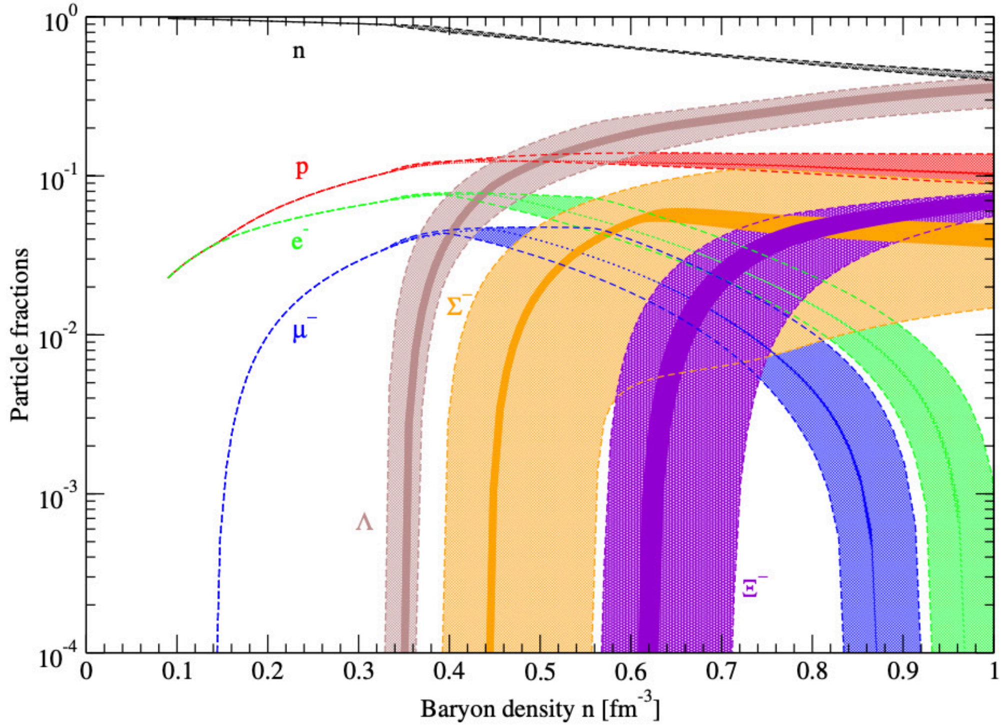


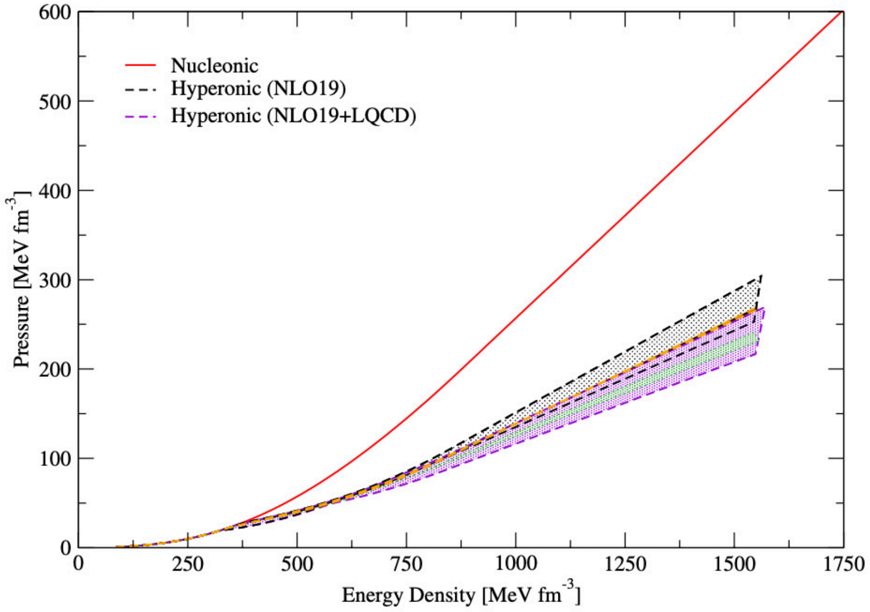


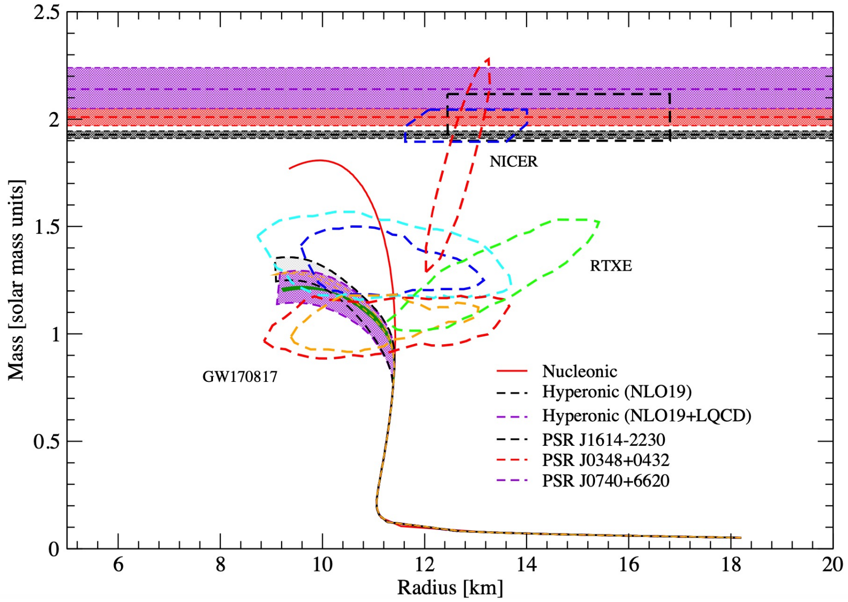
Several compensation mechanisms, always leading to a soft EoS and keeping the maximum mass low: A stiffer nucleonic EoS leads to an earlier onset of hyperons and thus enhanced softening due to their presence. The resulting maximum mass is surprisingly quite insensitive to the purely nucleonic EoS.

Inclusion of strangeness $S = -2$ $\Lambda\Lambda$ & $N\Xi^-$ channels

- NN (Av18)+ UIX NNN (K=180 MeV)
- NY (Tuned NLO19 to femtoscopic data)
- $\Lambda\Lambda$+$N\Xi^-$ (LQCD)







$\Lambda\Lambda$+$N\Xi^-$ innteractions induce an additional softening of the EoS & consequently an additional reduction of the NS mass

The final message of this talk

The purpose of this talk was to review briefly some of the effects of hyperons on the properties of neutron, particularly, on

- ✧ EoS & maximum mass of neutron stars ("hyperon puzzle" & its possible solutions)
- ✧ Transport coefficients of neutron star matter (thermal conductivity, shear viscosity)
- ✧ Neutron star cooling & r-mode instability

In a second part we summarized some of the experimental constraints of YN & YY interactions was presented with a special emphasis in the recent constraints arising from femtoscopy

✧ You for your time & attention

✧ Laura, Alexander, Philip & Tim for their kind invitation