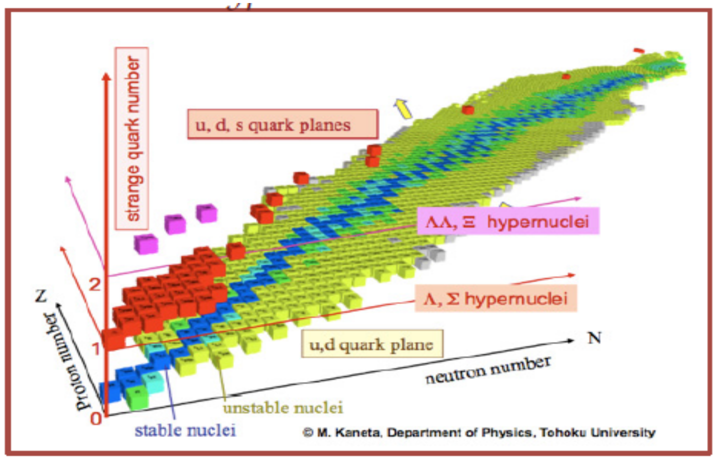
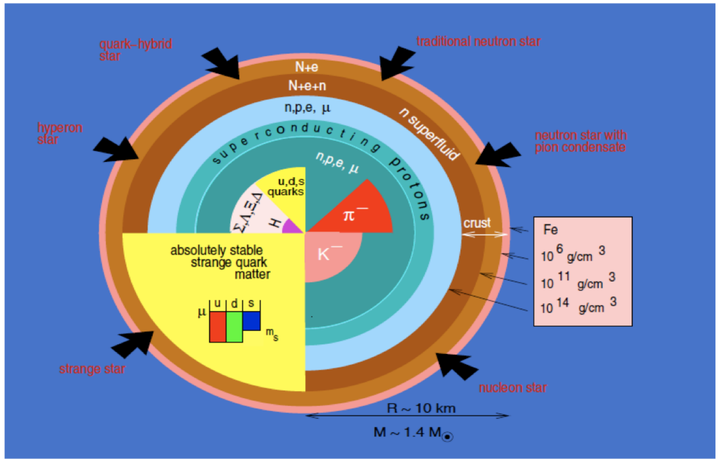


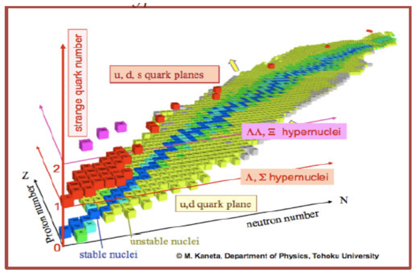


Hyperons in Nuclei and Neutron Stars

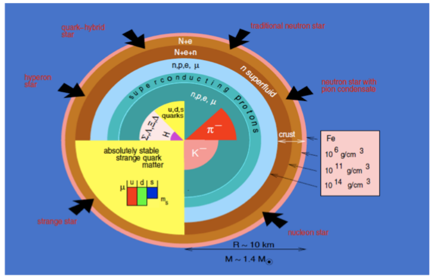
Laura Tolós

Institute of Space Sciences
CSIC IEEC
Consejo Superior de Investigaciones Científicas

based on
Laura Tolos and Laura Fabbietti,
Prog. Part. Nucl. Phys. 112 (2020) 103770, 2002.09223 [nucl-ex]



Outline



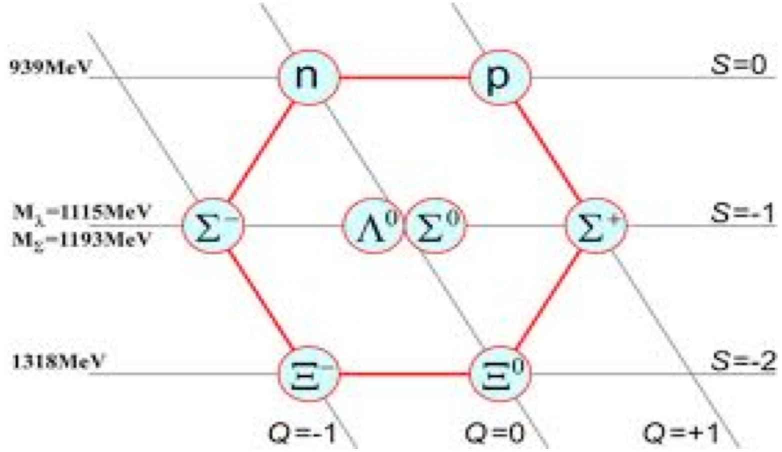
- Hyperons and where to find them
- YN and YY interactions
- Hypernuclei
- Hyperons in matter
- Hyperons and Neutron Stars
- Present and Future

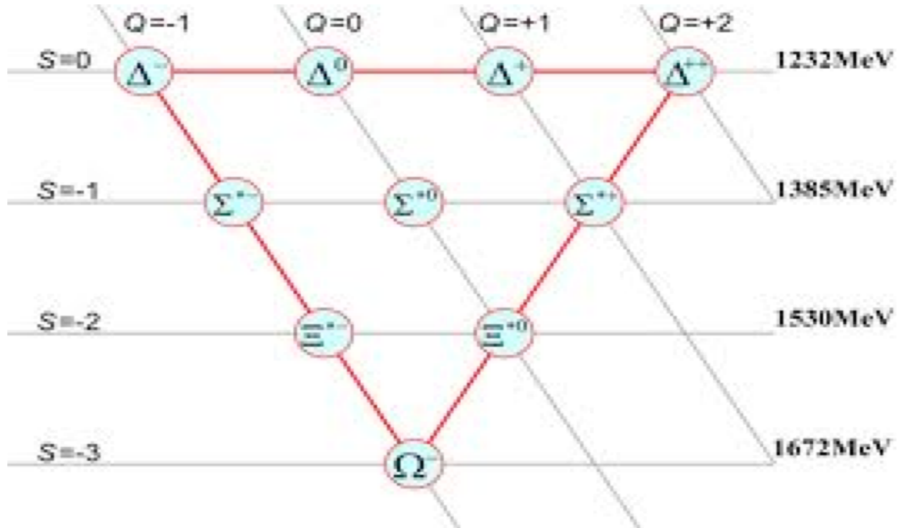
Hyperons and where to find them

A hyperon is a baryon containing one or more strange quarks

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

credit: I. Vidana





On Earth: Hypernuclei

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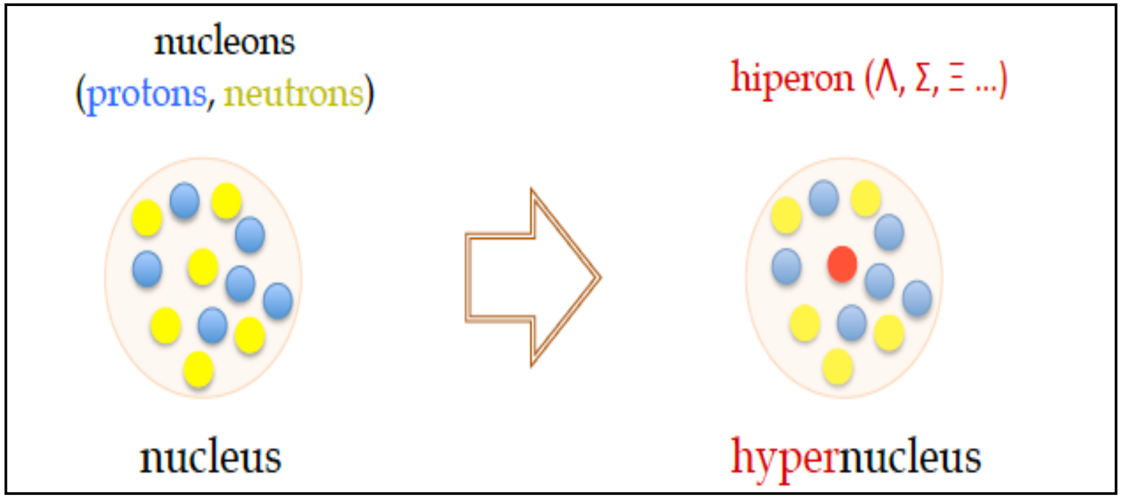
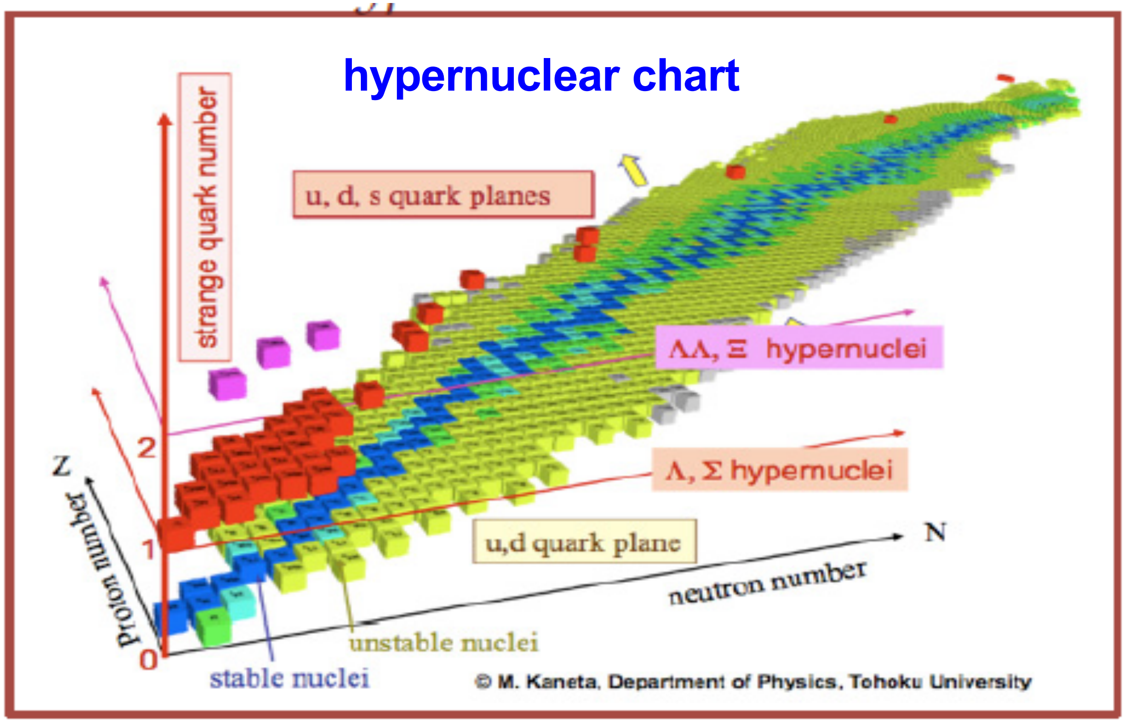


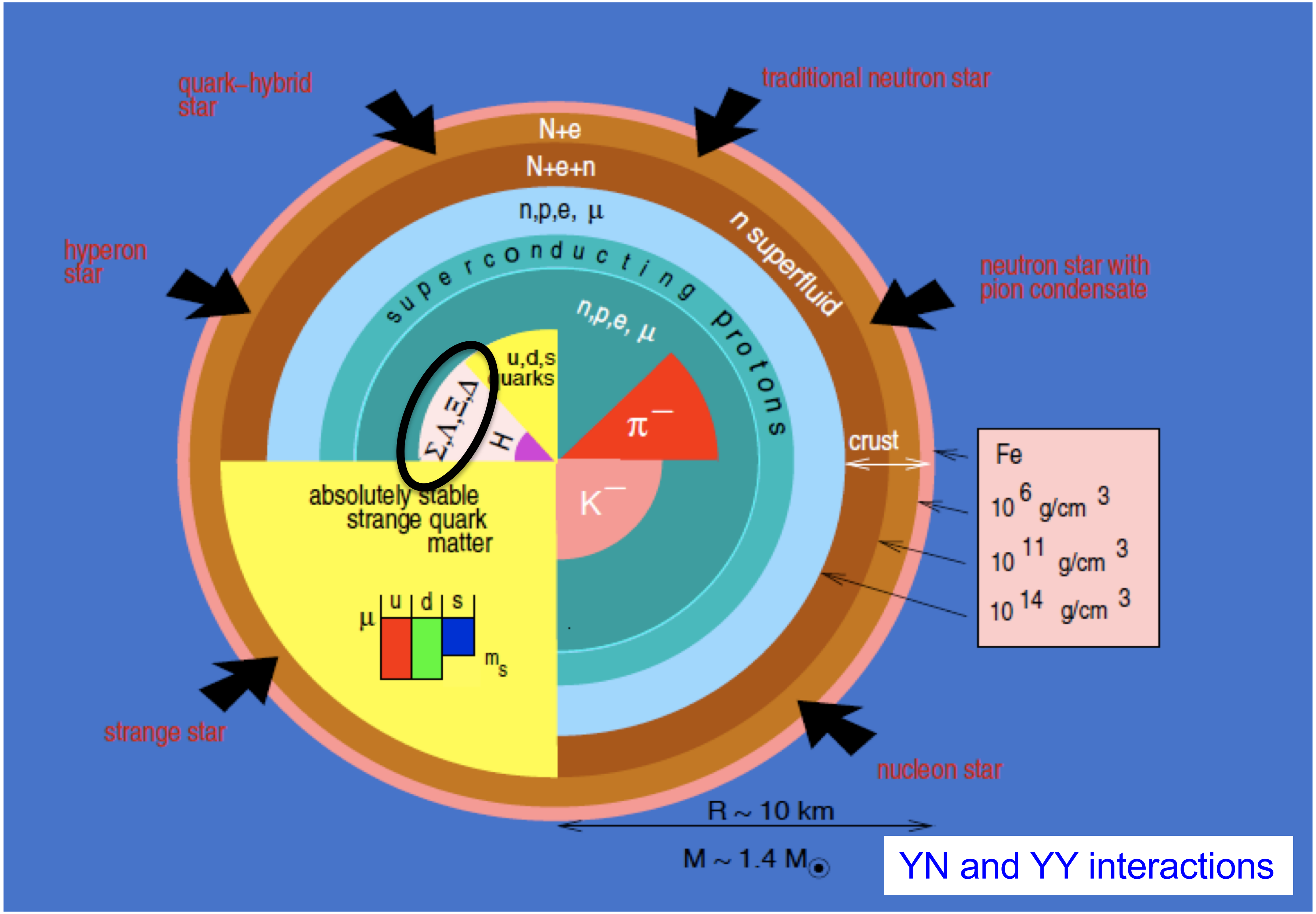
credit: A. Parreno

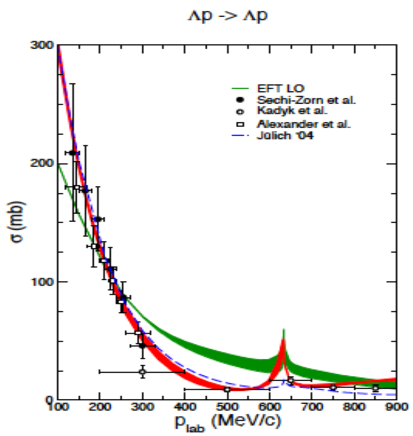


The study of hypernucleus allows for

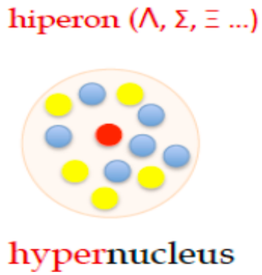
- new spectroscopy
- information on strong and weak interactions between hyperons and nucleons

In Neutron Stars





YN and YY interactions



- Study strangeness in nuclear physics
- Provide input for hypernuclear physics and astrophysics

Scarce YN scattering data due to the short life of hyperons and the low-density beam fluxes

ΛN and ΣN: < 50 data points
ΞN very few events

NN: > 5000 data
for E_{lab}<350 MeV

Data from hypernuclei:

- more than 40 Λ-hypernuclei (ΛN attractive)
- few Λ Λ- hypernuclei ($\Lambda\Lambda$ weak attraction)
- few Ξ-hypernuclei (ΞN attractive)
- evidence of 1 Σ-hypernuclei ? (ΣN repulsive)

Theoretical approaches to YN and YY

- Meson exchange models (Juelich/Nijmegen models)

To build YN and YY from a NN meson-exchange model imposing $SU(3)_{flavor}$ symmetry

Juelich: Holzenkamp, Holinde, Speth '89; Haidenbauer and Meißner '05
Nijmegen: Maesen, Rijken, de Swart '89; Rijken, Nagels and Yamamoto '10

- Chiral effective field theory approach (Juelich-Bonn-Munich group)

To build YN and YY from a chiral effective Lagrangian similarly to NN interaction

Juelich-Bonn-Munich: Polinder, Haidenbauer and Meißner '06; Haidenbauer, Petschauer, Kaiser, Meißner, Nogga and Weise '13
Kohno '10; Kohno '18

- Quark model potentials

To build YN and YY within constituent quark models

Fujiwara, Suzuki, Nakamoto '07
Garcilazo, Fernandez-Carames and Valcarce '07 '10

- $V_{low\ k}$ approach

To calculate a "universal" effective low-momentum potential for YN and YY using RG techniques

Schaefer, Wagner, Wambach, Kuo and Brown '06

- Lattice calculations (HALQCD/NPLQCD)

To solve YN and YY interactions on the lattice

HALQCD: Ishii, Aoki, Hatsuda '07; Aoki, Hatsuda and Ishii '10; Aoki et al '12
NPLQCD: Beane, Orginos and Savage '11; Beane et al '12

Theoretical approaches to YN and YY

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NPLQCD: Beane, Orginos and Savage ‘11; Beane et al ’12

YN (and YY) meson-exchange models

Built from a NN meson-exchange model imposing $SU(3)_{flavor}$ symmetry

NIJMEGEN

(Nagels, Rijken, de Swart, Timmermans, Maessen..)

✓ Based on Nijmegen NN potential

✓ Momentum and Configuration Space

✓ Exchange of pseudoscalar, vector and scalar nonets

✓ SU(3) symmetry to relate YN to NN vertices

✓ Gaussian form factors

JUELICH

(Holzenkamp, Reube, Holinde, Speth, Haidenbauer, Meissner, Melnitchouck..)

✓ Based on Bonn NN potential

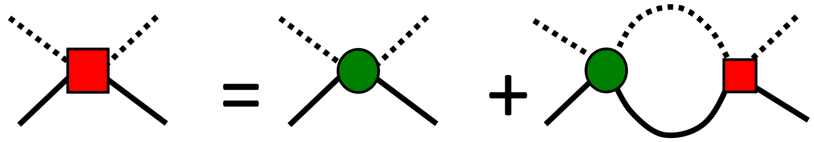
✓ Momentum Space, Full Energy Dependence & Non-localities

✓ Exchange of single mesons and higher order processes

✓ SU(6) symmetry to relate YN to NN vertices

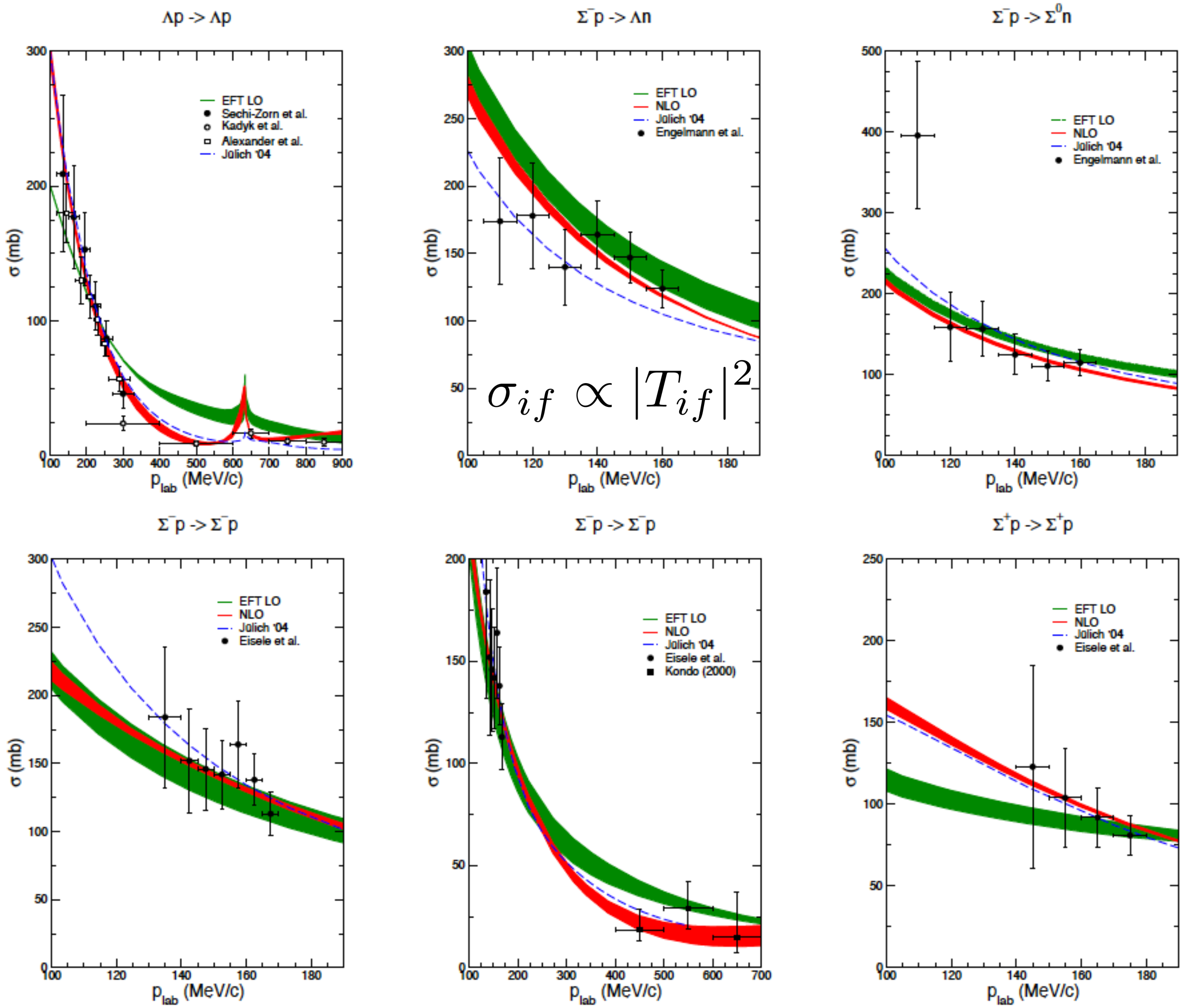
✓ Dipolar form factors

ΛN and ΣN scattering



LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.H., N. Kaiser, et al., NPA 915 (2013) 24
Jülich '04: J.H., U.-G. Meißner, PRC 72 (2005) 044005

$$T = V + V \frac{1}{E_0 - H_0 + i\eta} T$$

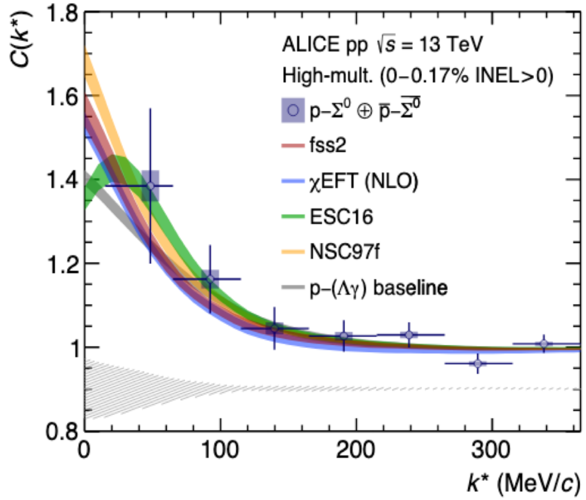


$$\sigma_{if} \propto |T_{if}|^2$$

New results from
femtoscopy for Σ^0p

$$C(k^*) = \mathcal{N} \times \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

$$k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$$



S. Acharya et al. 2019

YN (and YY) interactions in χEFT

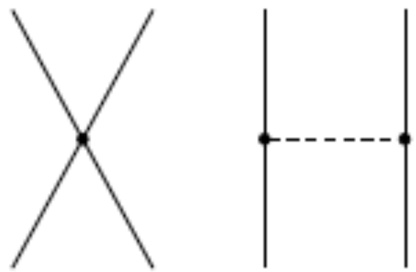
Baryon-Baryon interaction in SU(3) χEFT **a la Weinberg** (1990);

- **power counting** allowing for a systematic improvement by going to higher order
- derivation of **two- and three-baryon forces** in a consistent way

Degrees of freedom: **octet of baryons** (N, Λ ,Σ, Ξ) & **pseudoscalar mesons** (π,K,η)
Diagrams: **pseudoscalar-meson exchanges and contact terms**

credit: Haidenbauer

LO :

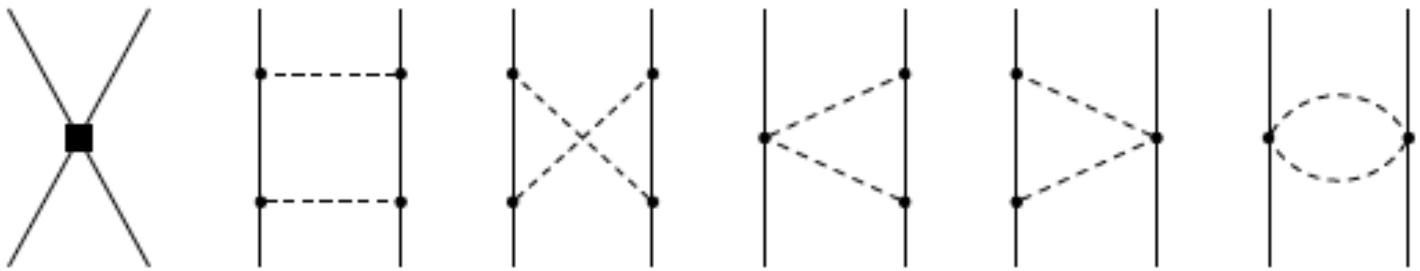


$$\nu = 2 - B + 2L + \sum_i v_i \Delta_i \ ,$$

$$\Delta_i = d_i + \frac{1}{2} b_i - 2 \ ,$$

B: number of incoming (outgoing) baryons
L: number of Goldstone boson loops
v_i: number of vertices with dimensión Δ_i
d_i: derivatives
b_i: number of internal baryons at vertex

NLO :



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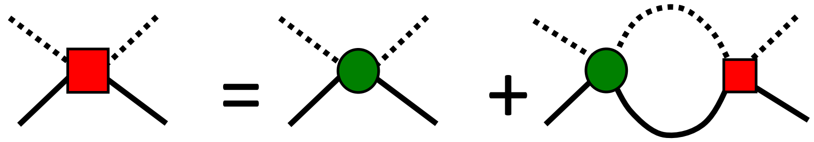
NLO: J.H., N. Kaiser, U.-G. Meißner, A. Nogga, S. Petschauer, W. Weise, NPA 915 (2013) 24

ΛN and ΣN scattering



$$T = V + V \frac{1}{E_0 - H_0 + i\eta} T$$

LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
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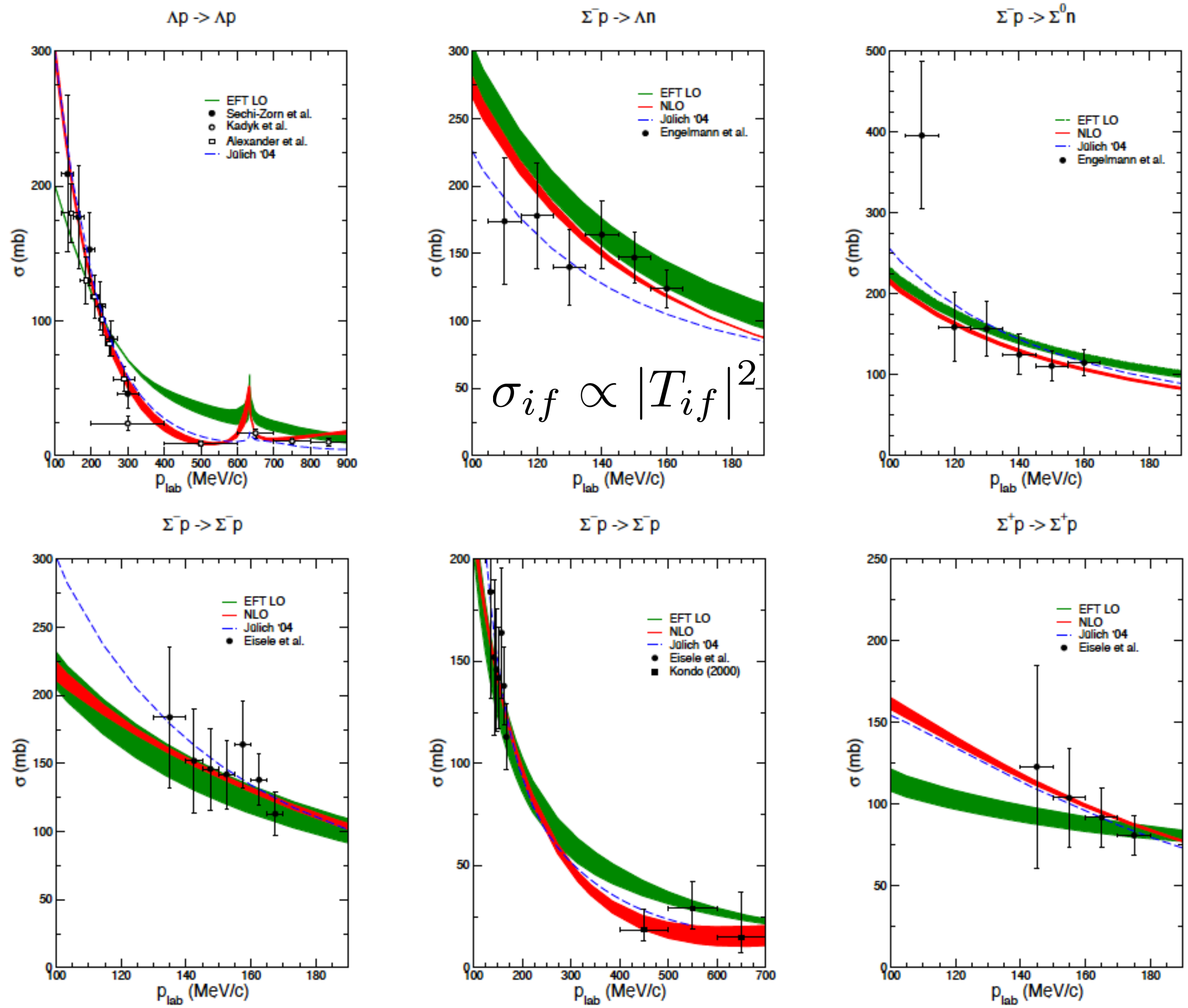
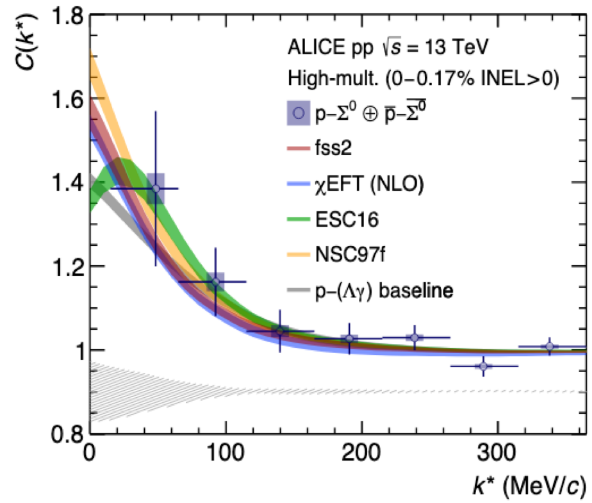


$$\sigma_{if} \propto |T_{if}|^2$$

New results from
femtoscopy for $\Sigma^0 p$

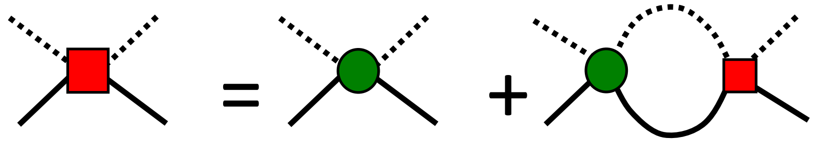
$$C(k^*) = \mathcal{N} \times \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

$$k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$$



S. Acharya et al. 2019

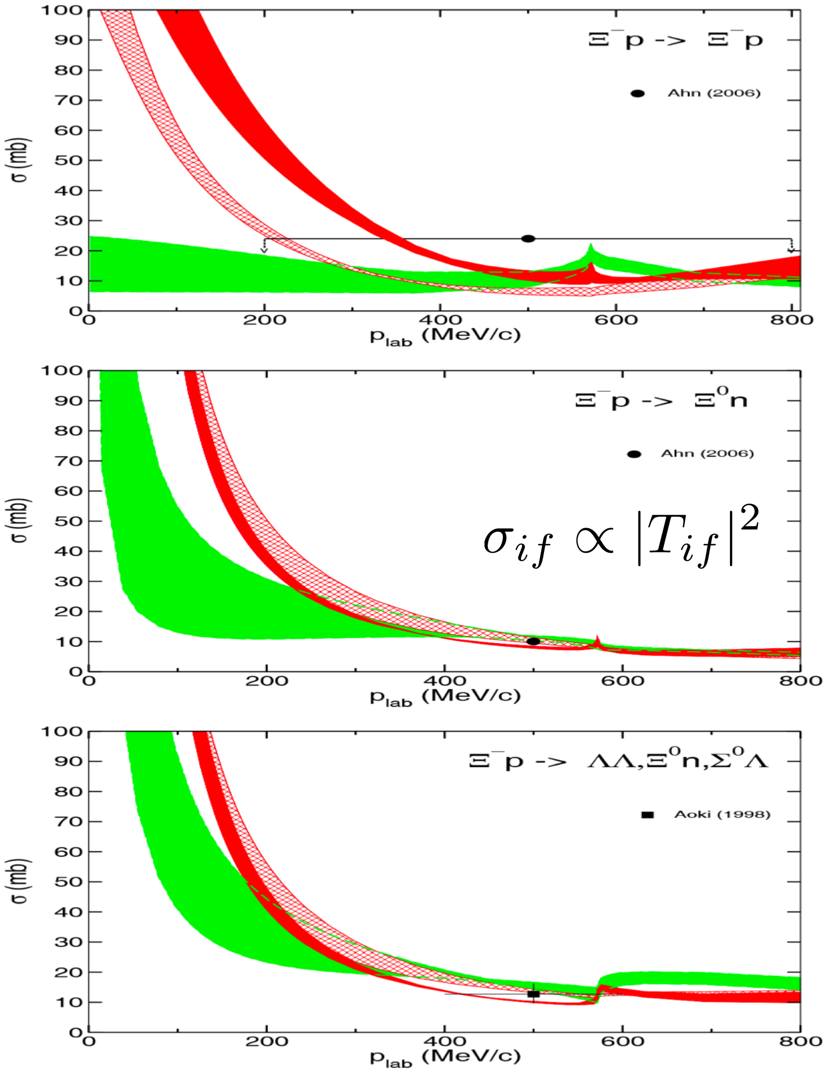
ΞN scattering



$$T = V + V\frac{1}{E_0 - H_0 + i\eta}T$$

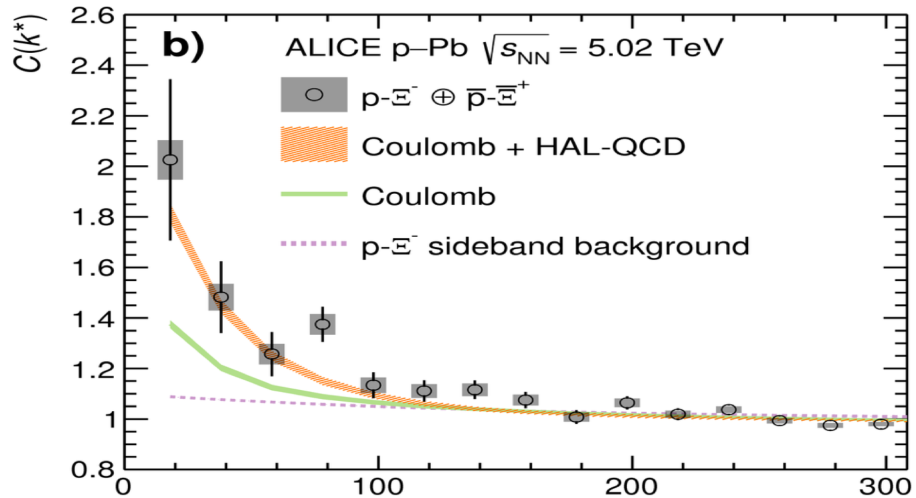
ΞN cross sections are small

J. Haidenbauer and
U.G. Meißner EPJA 55 (2019) 23



$$\sigma_{if} \propto |T_{if}|^2$$

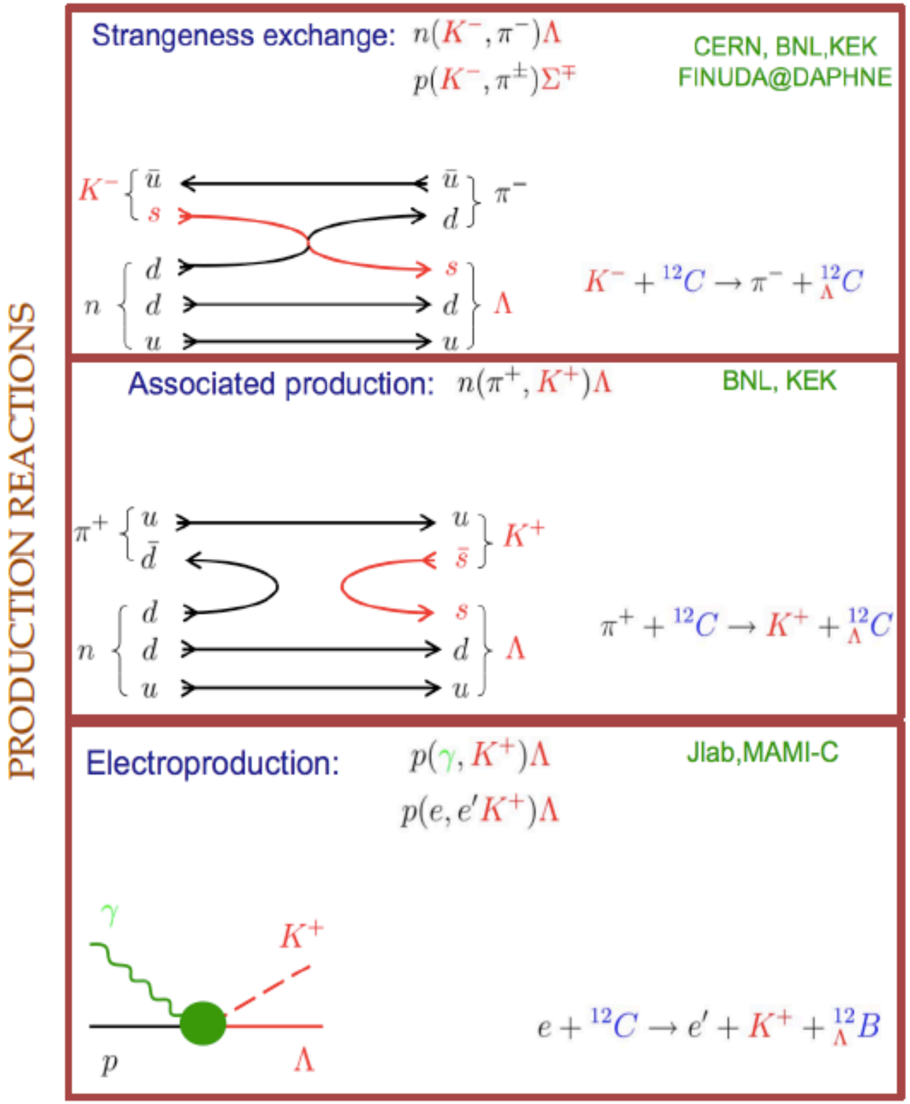
Scarce experimental information.
New results from femtoscopy



S. Acharya et al. 2019

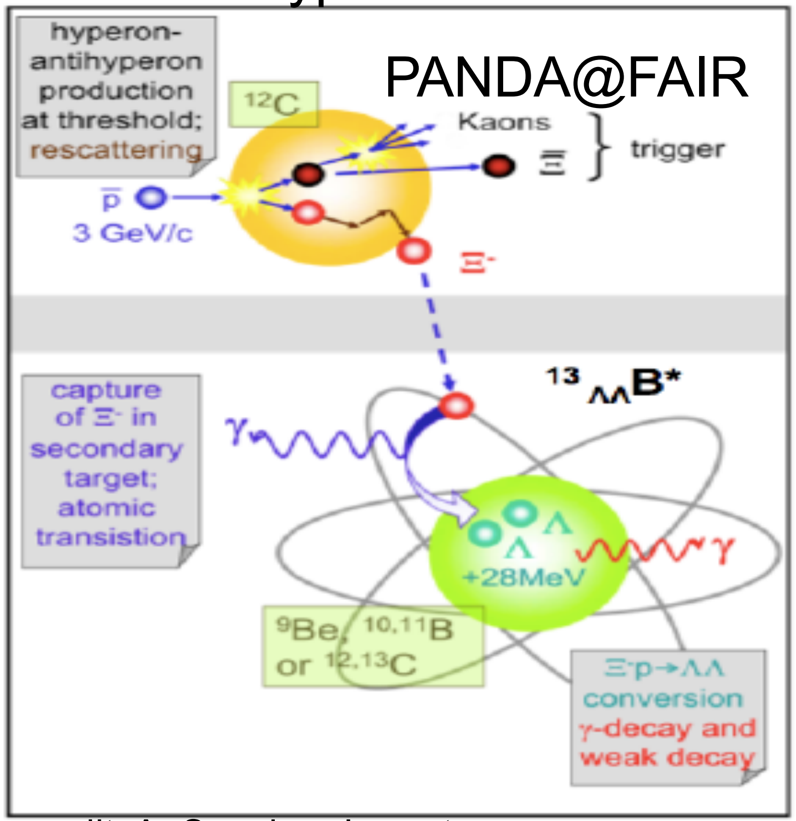
Hypernuclei

Λ hypernuclei



credit: A. Parreno

Double Λ hypernuclei



credit: A. Sanchez-Lorente

Also Ξ hypernuclei @ BNL, KEK

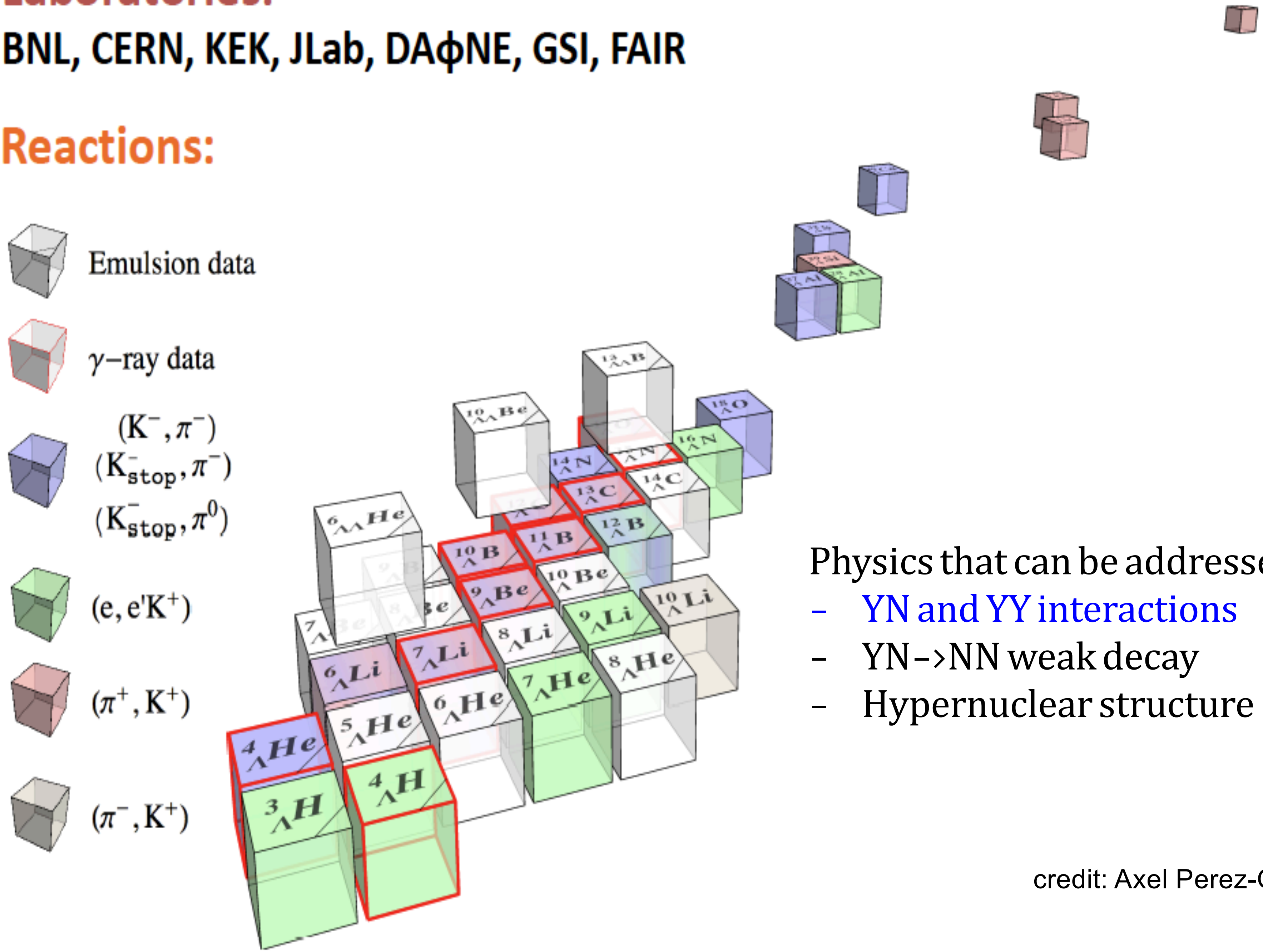
$$^{12}C(K^-,K^+)^{12}_{\Xi^-}Be$$

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

Laboratories:

BNL, CERN, KEK, JLab, DAΦNE, GSI, FAIR

Reactions:

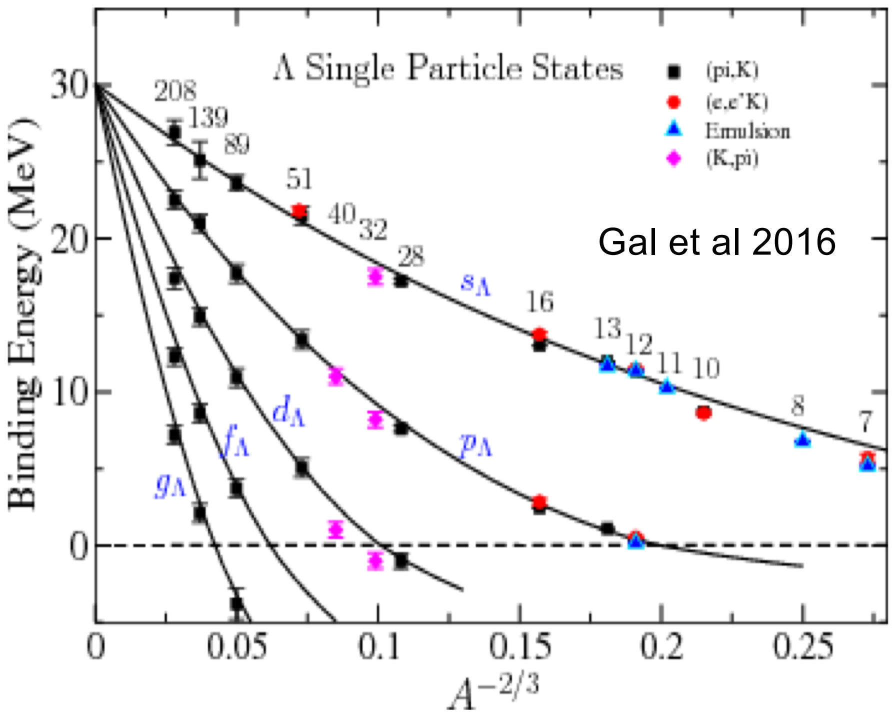


Physics that can be addressed：

- YN and YY interactions
- YN->NN weak decay
- Hypernuclear structure

credit: Axel Perez-Obiol

Binding energy of Λ hypernuclei

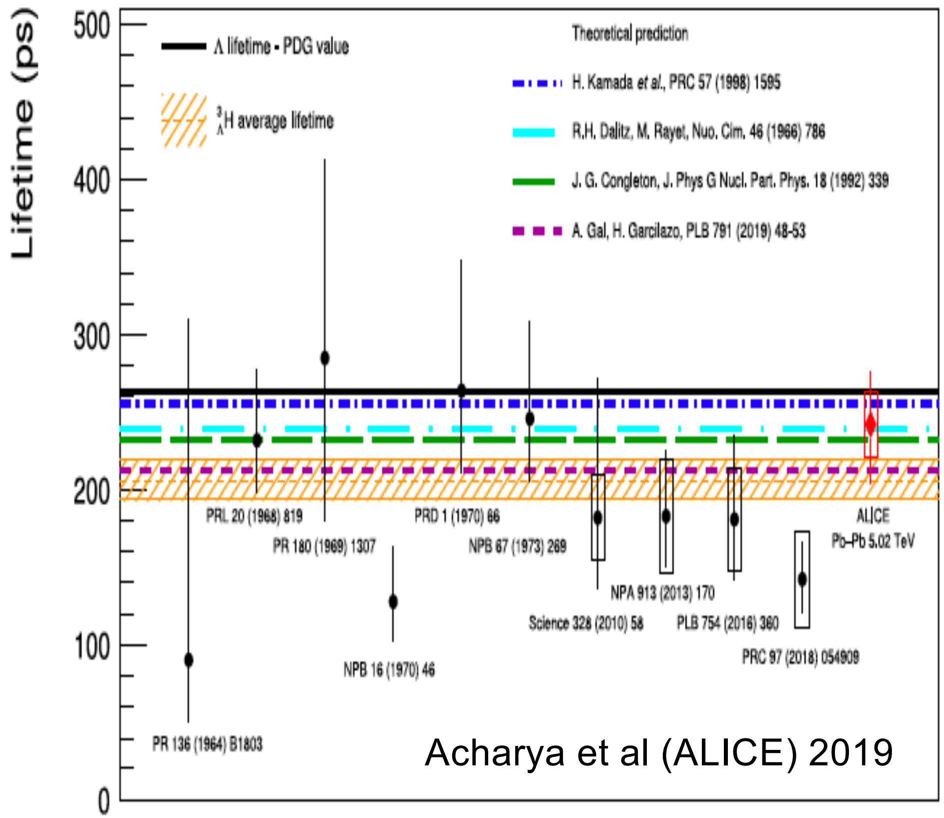


Binding energy of different hypernuclei as function of the mass number

Binding energy saturates at about -30 MeV for large nuclei

Single-particle model reproduces the data quite well Gal et al 2016

Hypertriton lifetime puzzle



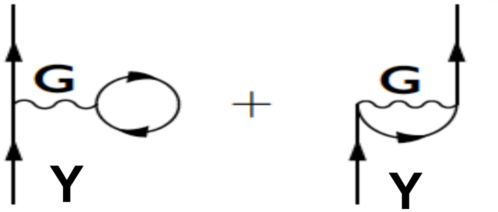
Expected $\tau({}^3_\Lambda H) = \tau(\Lambda)$

$\Leftrightarrow$ observed: $\tau({}^3_\Lambda H) < \tau(\Lambda)$?

Conflicting measurements by STAR and ALICE of the hypertriton lifetime triggered the revived experimental and theoretical interest

Hyperons in matter

Λ and Σ in dense matter



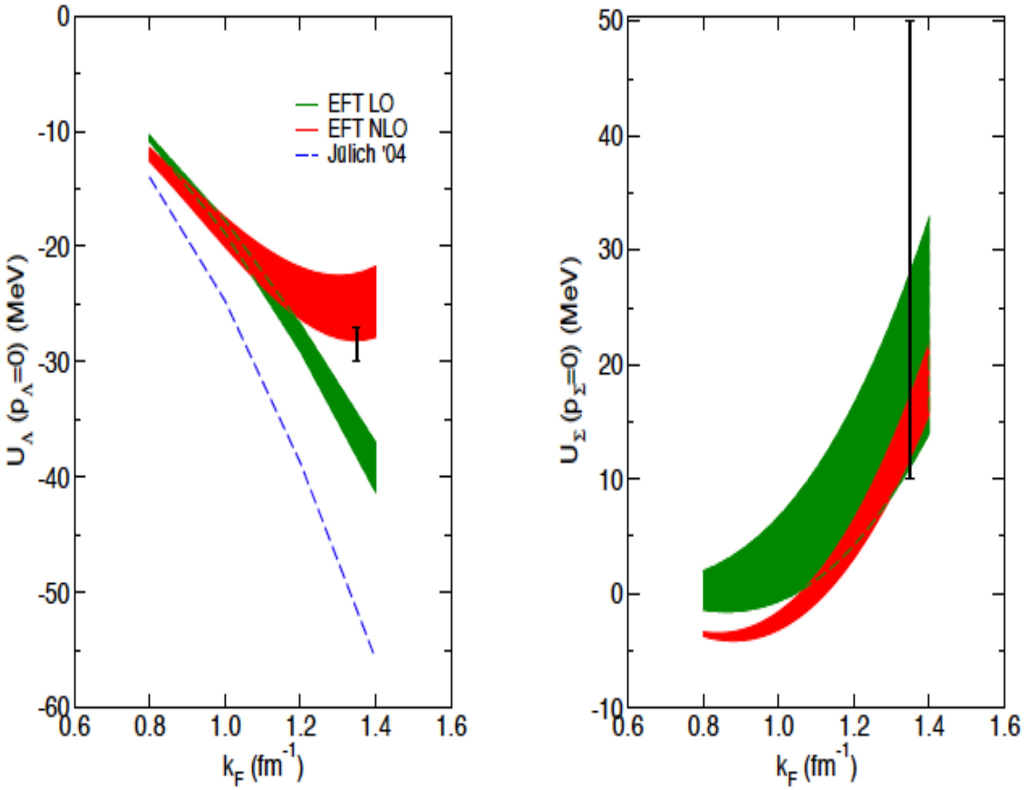
$$G = V + V \frac{Q_{\rm pauli}}{E_0 - H_0} G$$

$k_F = 1.35\ \mathrm{fm}^{-1}$ ($\rho_0 = 0.166\ \mathrm{fm}^{-3}$)

	EFT LO	EFT NLO
Λ [MeV]	550 ··· 700	500 ··· 650
$U_\Lambda(0)$	−38.0 ··· −34.4	−28.2 ··· −22.4
$U_\Sigma(0)$	28.0 ··· 11.1	17.3 ··· 11.9

- Empirical value of Λ binding in nuclear matter ~27-30 MeV

- ΣN (I=3/2): $^3S_1$-$^3D_1$ decisive for Σ properties in nuclear matter. YN data can be reproduced with attractive and repulsive $^3S_1$-$^3D_1$ interaction. It is chosen to be repulsive in accordance to data on Σ^- atoms and (π^-,K^+) inclusive spectra for Σ^- formation in heavy nuclei.
Lattice* supports repulsion!



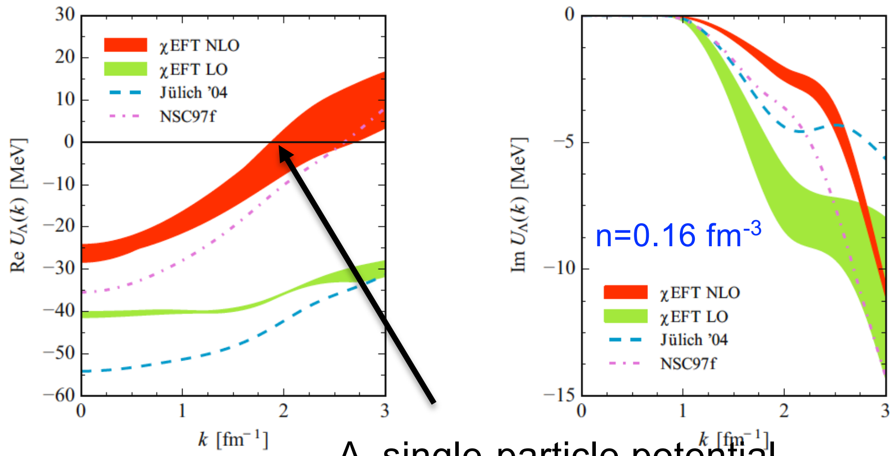
Haidenbauer and Meißner , NPA 936 (2015) 29

* Nemura et al EPJ Web of Conferences 175 (2018) 05030

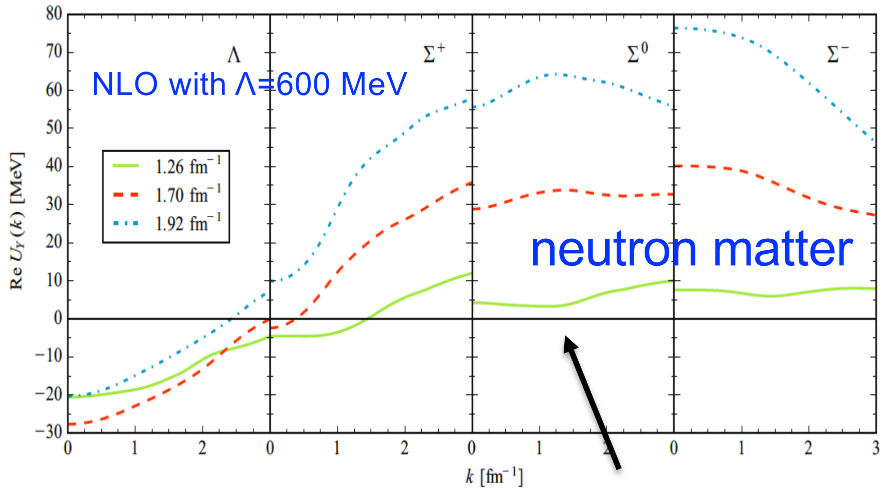
Improving on the calculation by using χEFT NN interaction and continuous choice in Brueckner-Hartree-Fock approach while investigating isospin-asymmetric matter

S. Petschauer, J. Haidenbauer, N. Kaiser, U.G. Meißner and W. Weise EPJA 52 (2016) 15

symmetric nuclear matter

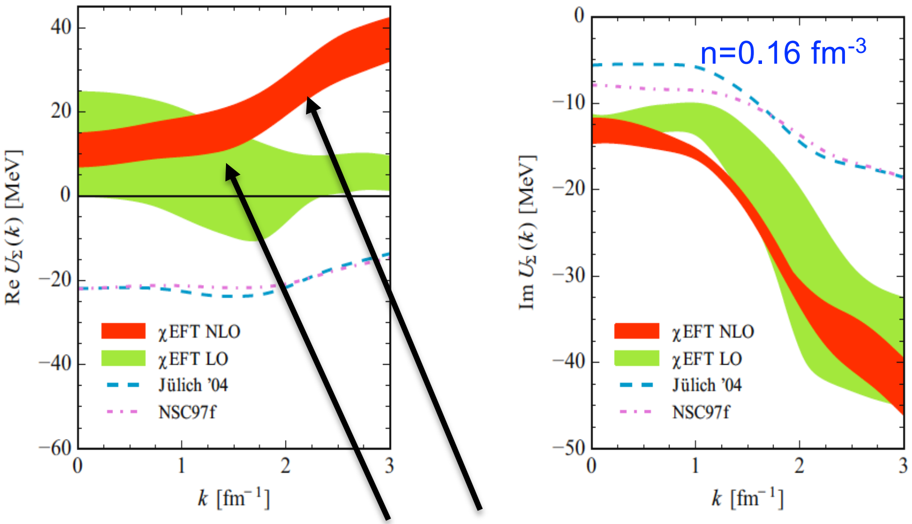


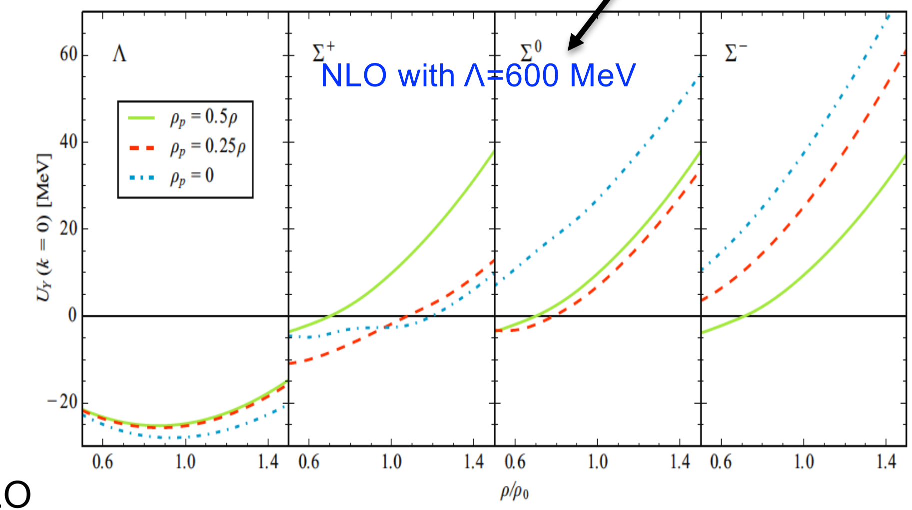
Λ single-particle potential at NLO turns repulsive k~2 fm $^{-1}$



neutron matter

strong isospin dependence of the ΣN interaction



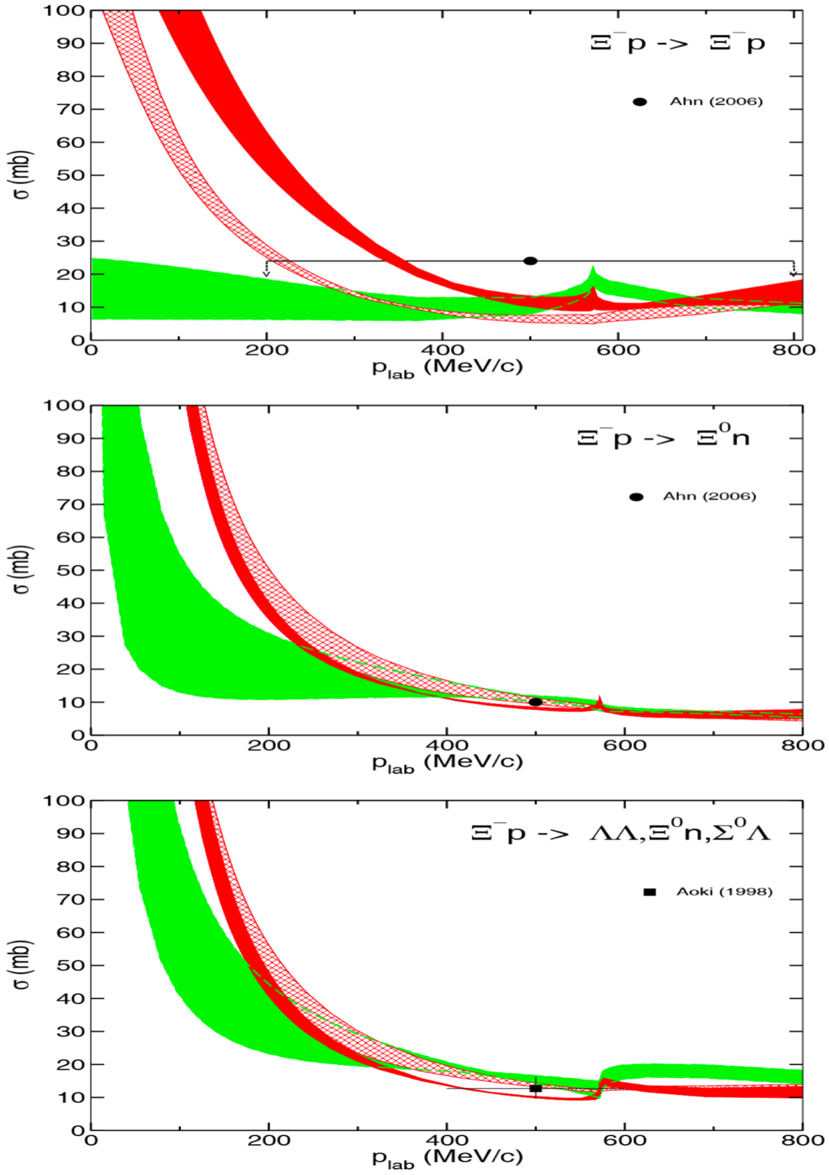


Σ-nuclear potential is moderately repulsive for LO and NLO

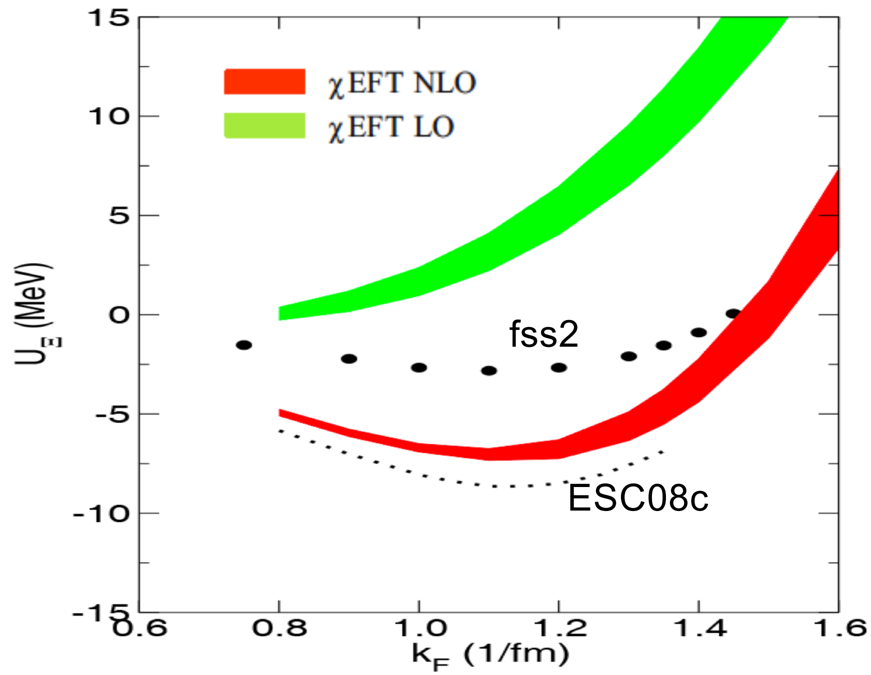
Ξ in dense matter

J. Haidenbauer and
U.G. Meißner EPJA 55 (2019) 23

ΞN cross sections are small



Ξ in dense matter

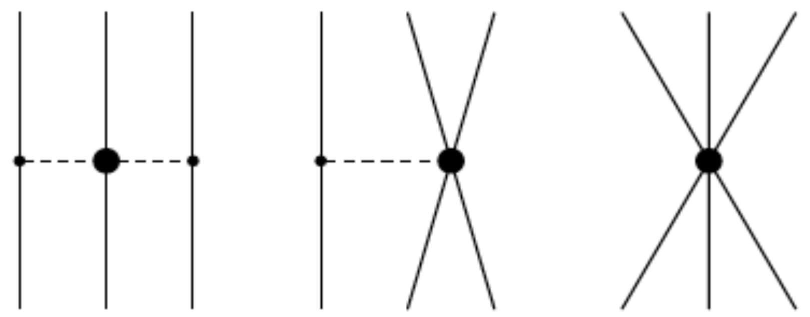


Moderately attractive Ξ-nuclear interaction, with $U_\Xi(0,k_{F0})$ ~ -3 to -5 MeV.
Smaller than $U_\Xi(n_0)$ ~-14 MeV Khaustov et al'00
and in line with other BHF studies with phenomenological ΞN potentials

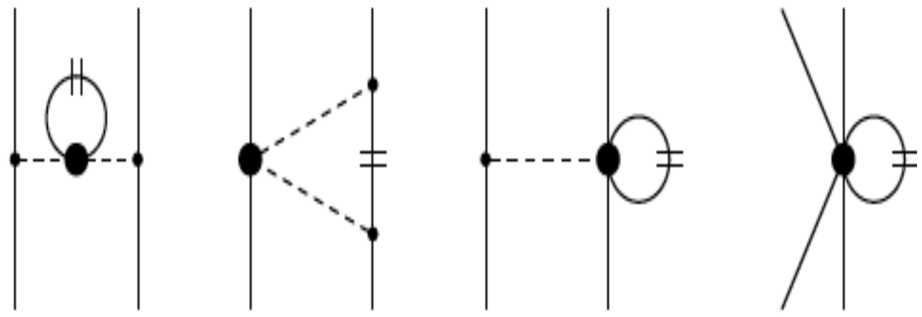
Λ in dense matter: including three-body forces

Three-body forces are required to reproduce few-nucleon binding energies, scattering observables and nuclear saturation in non-relativistic many-body approaches

Three-body force (nominally at N²LO)



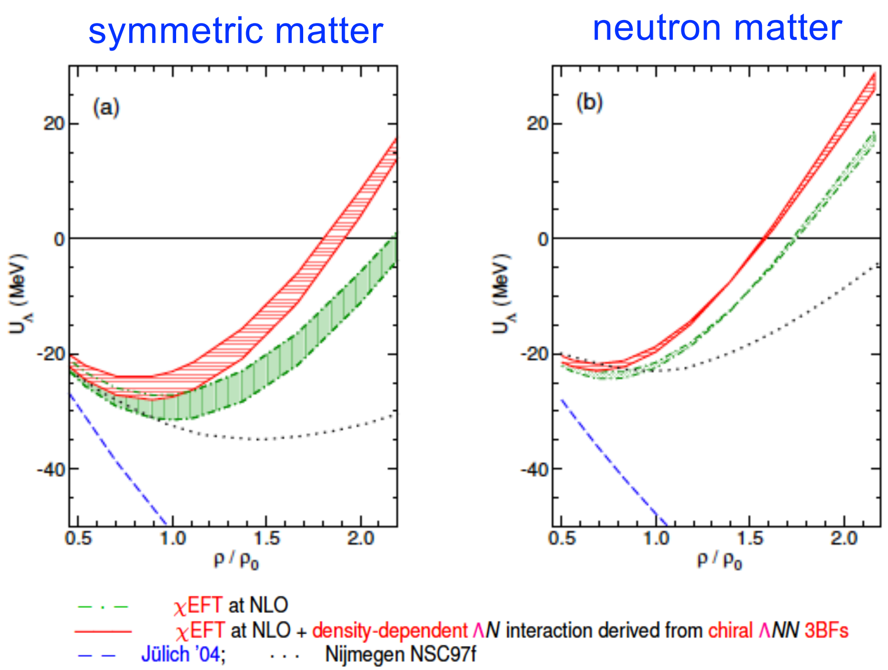
To use it in many-body calculations, such as BHF, one has to construct a density-dependent two-body interaction



closing two baryon lines summing over the Fermi sea

credit: Haidenbauer

Λ in dense matter



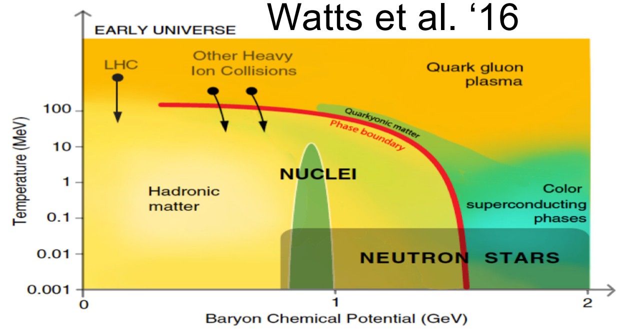
χEFT gives little attraction or even repulsion for $n > n_0$

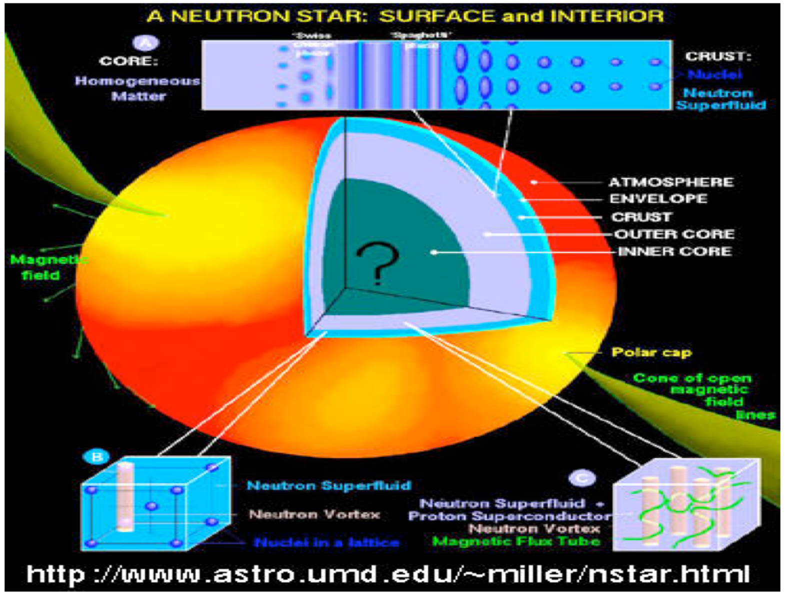
In neutron stars, hyperons will appear at high density!!

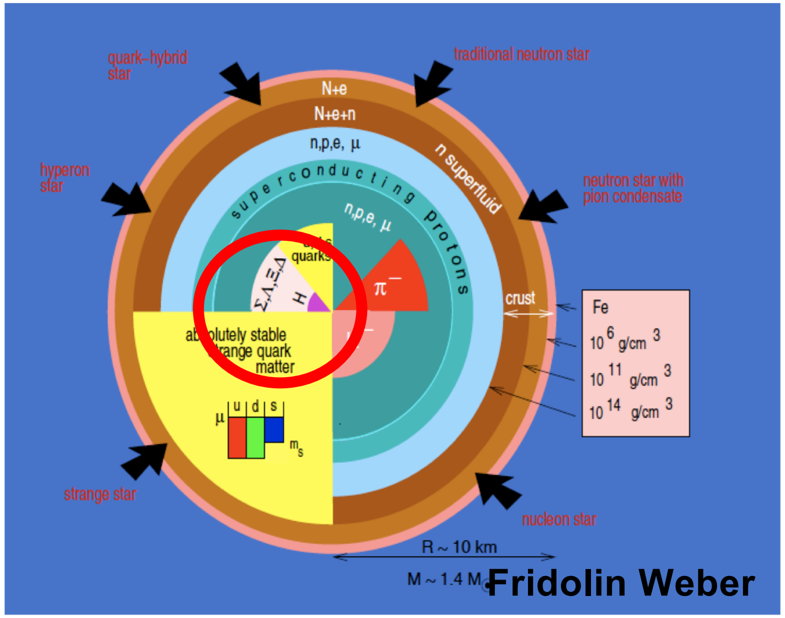
Solution of the Hyperon Puzzle?

J. Haidenbauer, U.G. Meißner, N. Kaiser and W. Weise EPJA 53 (2017) 121

Hyperons and Neutron Stars





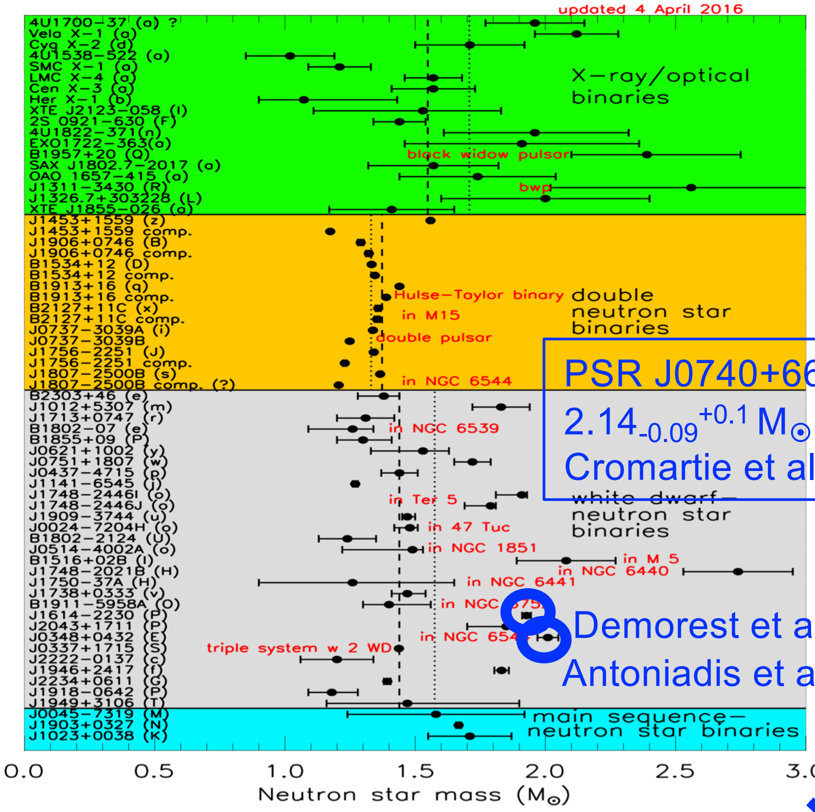


- produced in core collapse supernova explosions, usually observed as pulsars
- usually refer to compact objects with $M \approx 1\text{-}2\ M_\odot$ and $R \approx 10\text{-}12$ Km
- extreme densities up to $5\text{-}10\ \rho_0$ ($n_0 = 0.16\ \mathrm{fm}^{-3} \Rightarrow \rho_0 = 3 \bullet 10^{14}\ \mathrm{g/cm}^3$)
- magnetic field : $B \sim 10^{8..16}$ G
- temperature: $T \sim 10^{6\ldots11}$ K
- observations: masses, radius (?), gravitational waves, cooling…

Observations

Masses

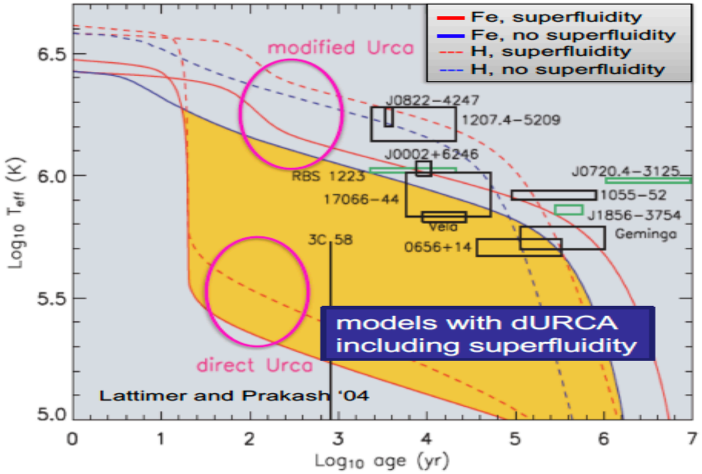
Lattimer '16



PSR J0740+6620
$2.14_{-0.09}^{+0.1}\ M_\odot$
Cromartie et al '19

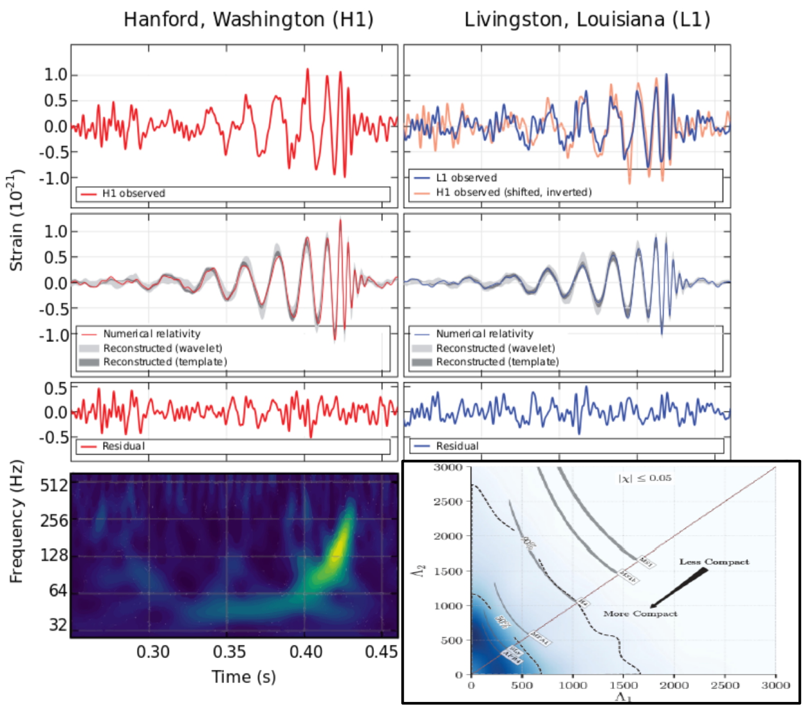
Demorest et al '10
& Antoniadis et al '13

Cooling



GW170817

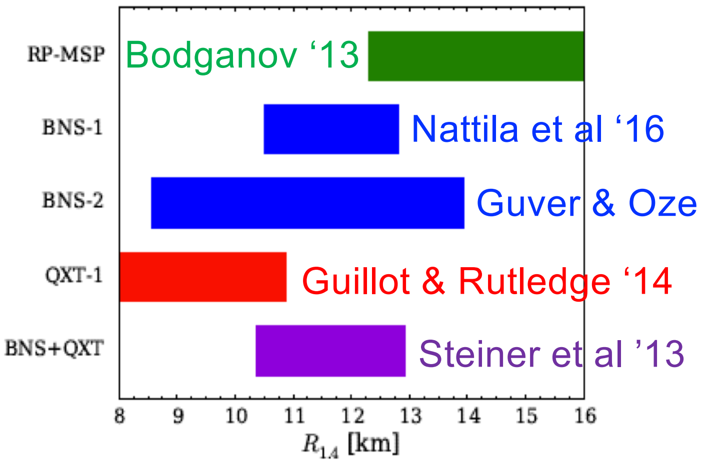
Abbot et al. (LIGO-VIRGO) '17 '18



..also GW250419?

Radius

Fortin et al. '15

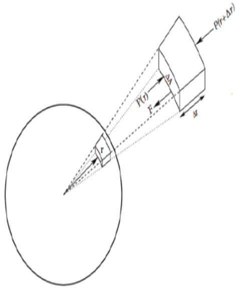


NICER
PSR J0030+0451

$R_{eq}=12.71_{-1.19}^{+1.14}$ km
$M=1.34_{-0.16}^{+0.15}\ M_\odot$
Riley et al. '19

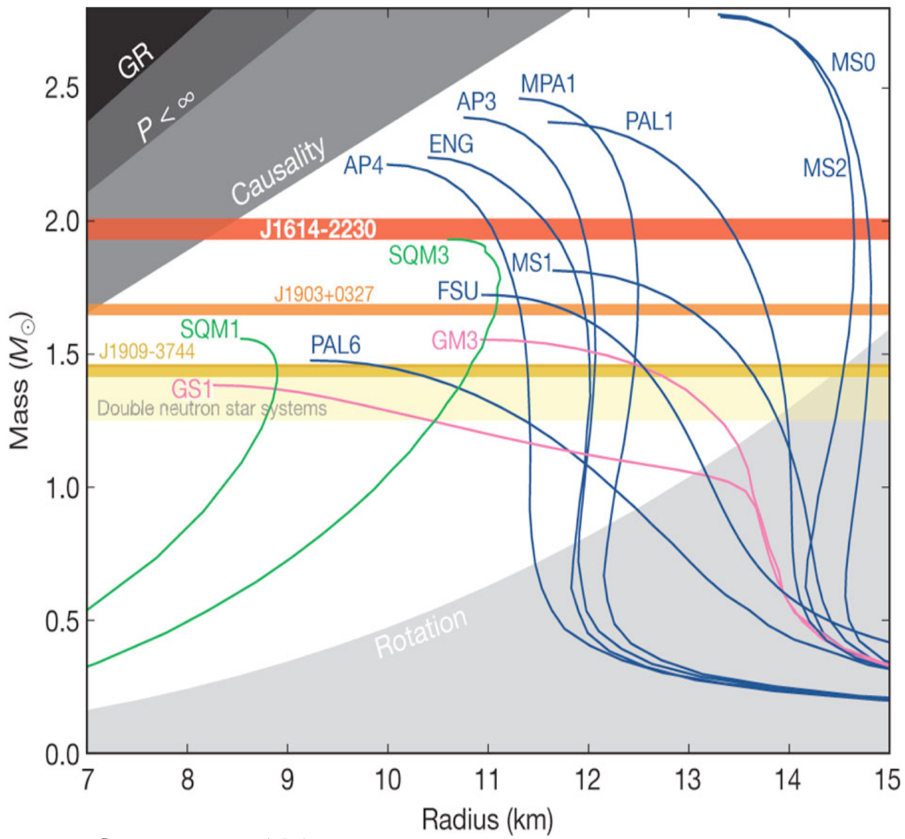
$R_{eq}=13.02_{-1.06}^{+1.24}$ km
$M=1.44_{-0.14}^{+0.15}\ M_\odot$
Miller et al. '19

Mass-Radius Relation



$$\frac{dP}{dr} = -\frac{Gm\epsilon}{c^2r^2}\left(1+\frac{P}{\epsilon}\right)\left(1+\frac{4\pi r^3 P}{c^2 m}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1}$$

$$\frac{dm}{dr} = \frac{4\pi r^2 \epsilon}{c^2}$$



Ozel et al '16

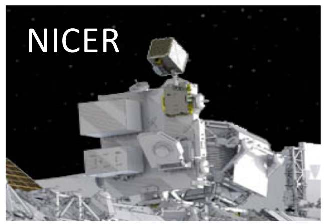
- primary ingredient:

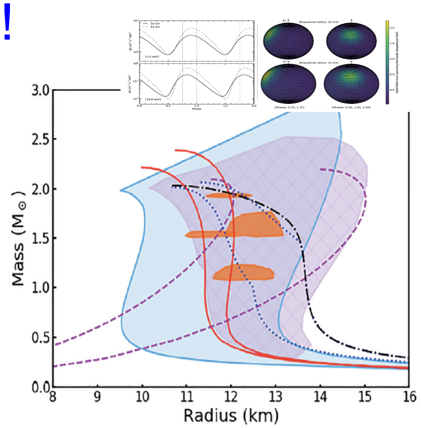
EoS: $\epsilon(n)$, $P(n)$, $P(\epsilon)$
in charge neutral β-stable matter

- some constraints:

 - Schwarzschild limit (GR)
   $R \geq 2\ GM/c^2$
 - causality limit for EoS
   $R \geq 2.9\ GM/c^2$
 - mass-shedding limit
   $R < (GM/2\pi)^{1/3}/\upsilon^{2/3}$

Need of simultaneous mass-radius measurements to constrain EoS !!!





Watts et al. (LT) '19

The Nucleonic Equation of State

The Equation of State (EoS) is a relation between thermodynamic variables describing the state of matter

Microscopic Ab-initio Approaches:
based on solving the many-body problem starting from two- and three-body interactions

- *Variational method: APR, CBF,..*
- *Quantum Montecarlo : AFDMC..*
- *Coupled cluster expansion*
- *Diagrammatic: BBG (BHF), SCGF..*
- *Relativistic DBHF*
- *RG methods: SRG from χEFT..*
- *Lattice methods*

Advantage: systematic addition of higher-order contributions
Disadvantage: applicable up to?
(SRG from χEFT ~ 1-2 n_0)

Phenomenological Approaches:
based on density-dependent interactions adjusted to nuclear observables and neutron star observations

- *Non-relativistic EDF: Skyrme..*
- *Relativistic Mean-Field (RMF) and Relativistic Hartree-Fock (RHF)*
- *Liquid Drop Model: BPS, BBP,..*
- *Thomas-Fermi model: Shen*
- *Statistical Model: HWN,RG,HS..*

Advantage: applicable to high densities beyond n_0
Disadvantage: not systematic

What about Hyperons?

credit: Vidana

First proposed in 1960 by Ambartsumyan & Saakyan

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

Traditionally neutron stars were modeled by a uniform fluid of neutron rich matter in β-equilibrium

$$n \rightarrow p\, e^- \,\bar{\nu}_e$$

$$p\, e^- \rightarrow n\, \nu_e$$

but more exotic degrees of freedom are expected, such as **hyperons**, due to:

- high value of density at the center and
- the rapid increase of the nucleon chemical potential with density

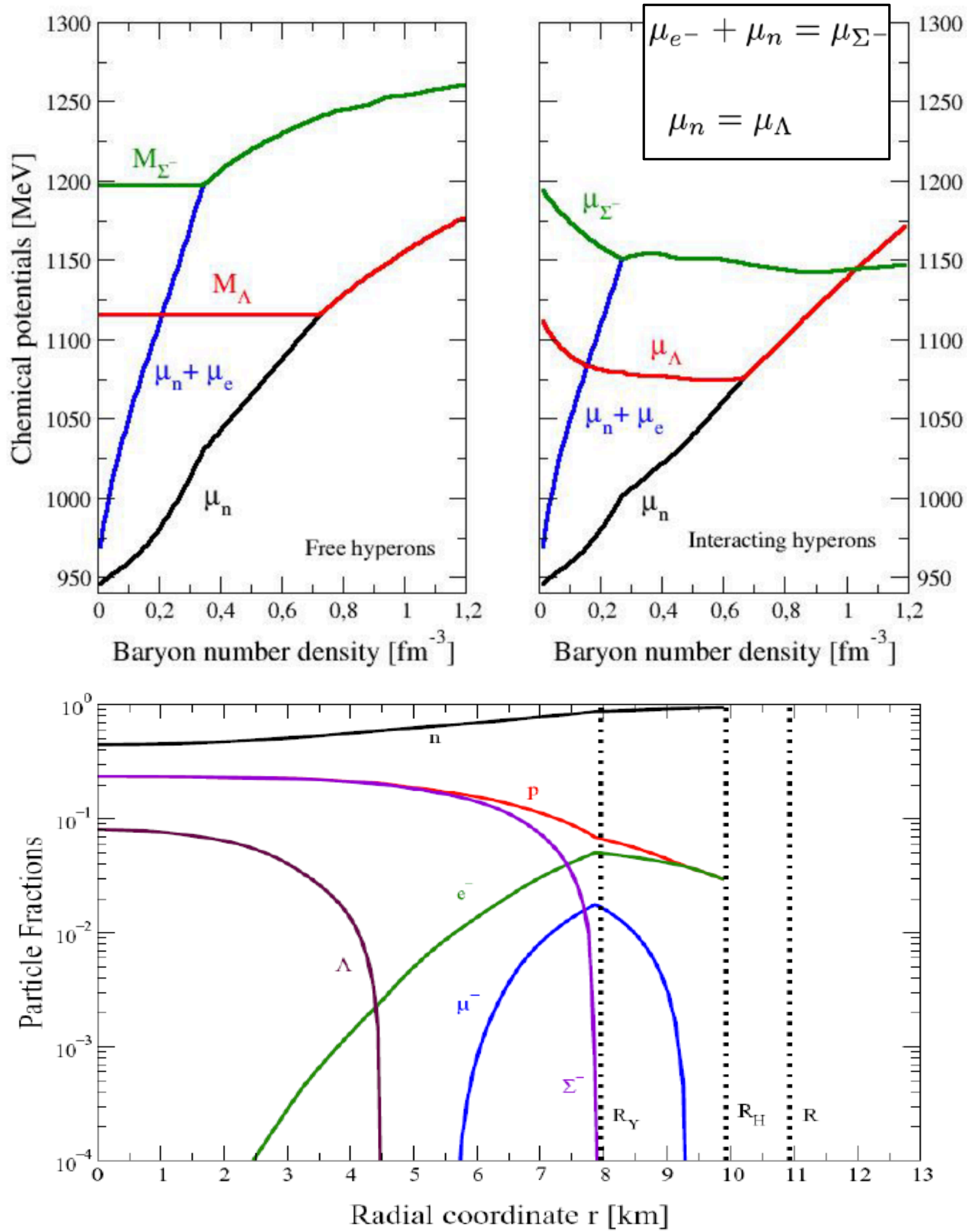
Hyperons might be present at $n \sim (2\text{-}3)n_0$!!!

β-stable hyperonic matter

μ_N is large enough to make N->Y favorable

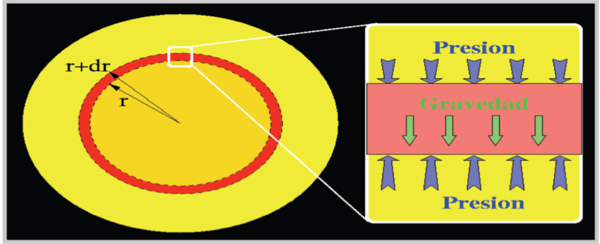
$$n + n \rightarrow n + \Lambda$$
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$
$$n + n \rightarrow p + \Sigma^-$$
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

$$\mu_i = b_i \mu_n - q_i \mu_e$$
$$\sum_i x_i q_i = 0$$

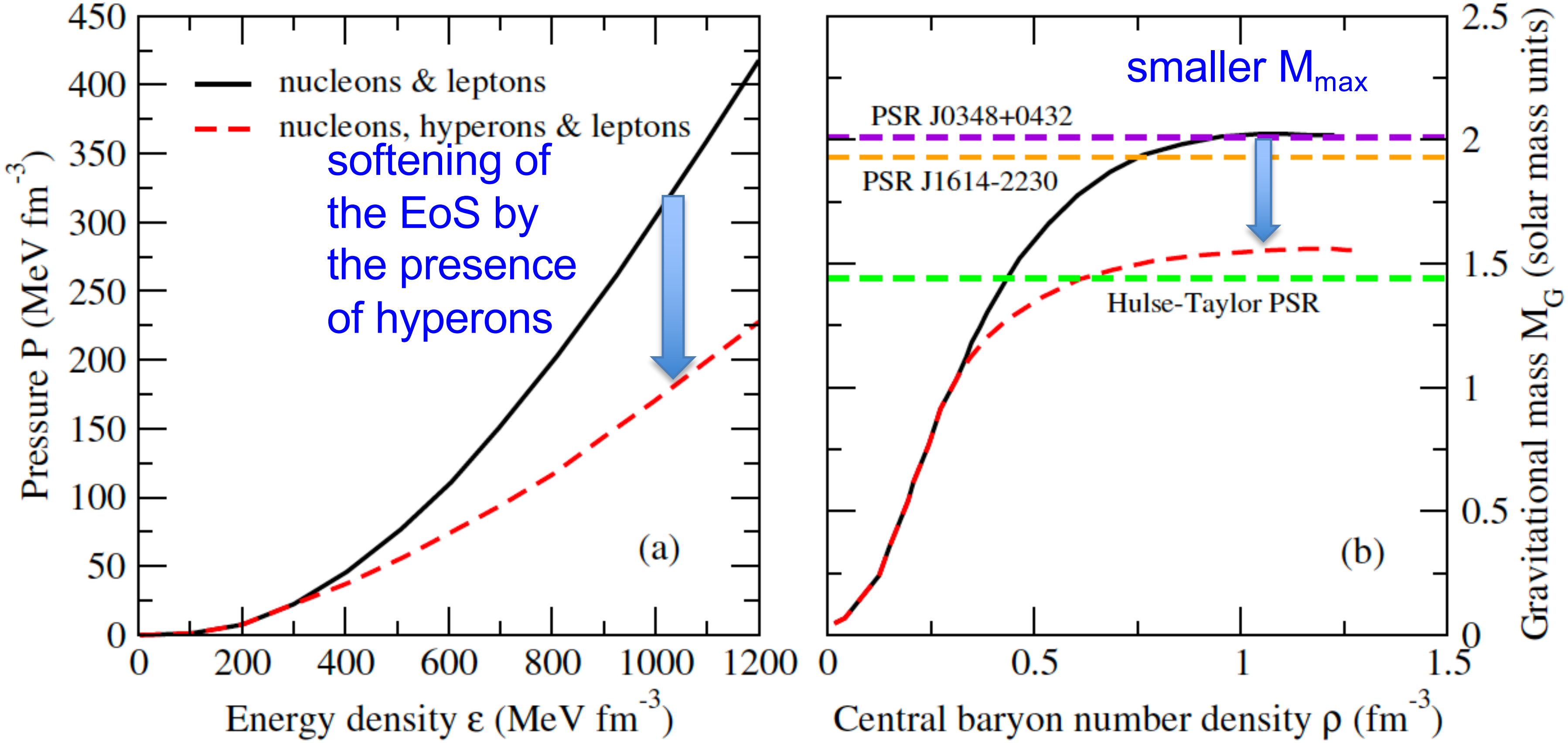


credit: Vidana

Inclusion of hyperons….



Credit:
Dani P. Page



….. induces a strong softening of the EoS that leads to $\mathbf{M_{max} < 2M_\odot}$

Chatterjee and Vidana '16
Vidana '18

The Hyperon Puzzle

The Hyperon Puzzle

Scarce experimental information:

- data from several single Λ- and few Ξ- hypernuclei, and few double Λ hypernuclei

- few YN scattering data (~ 50 points) due to difficulties in preparing hyperon beams and no hyperon targets available

- YN data from femtoscopy

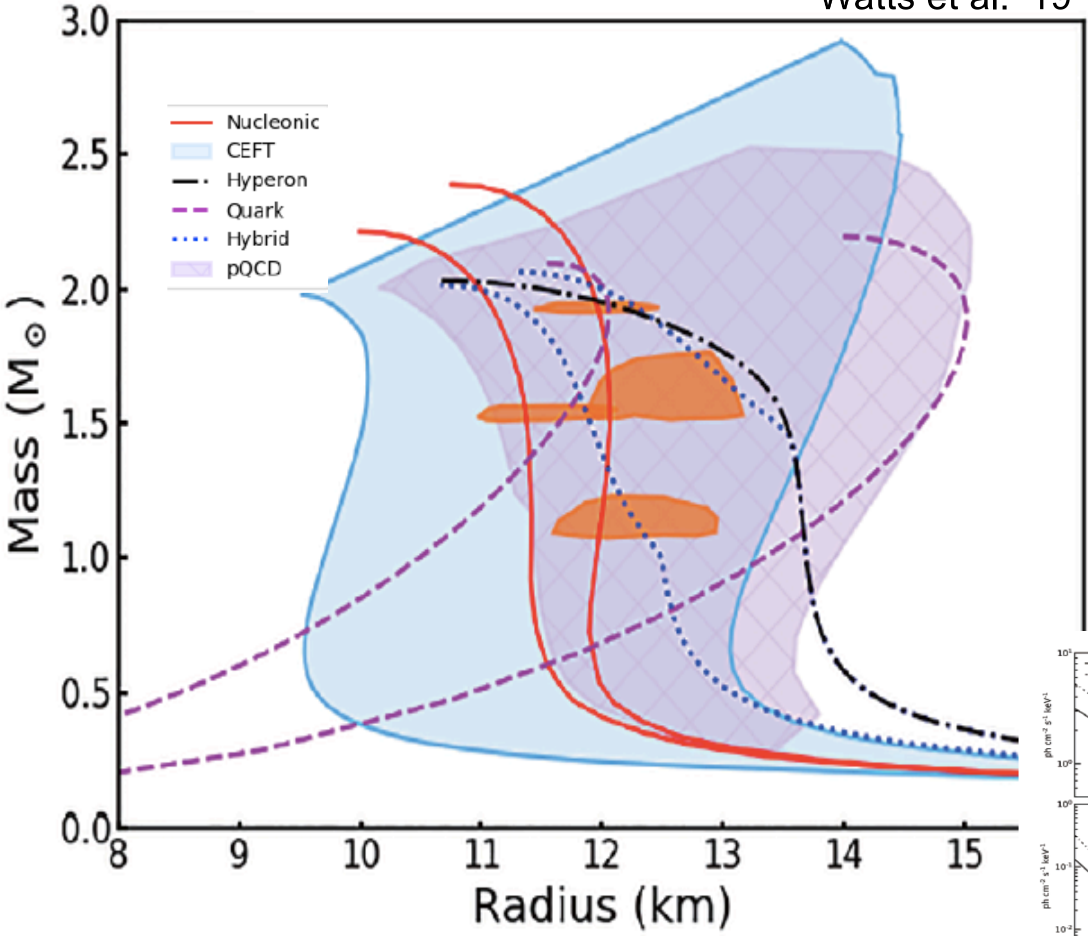
The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to **maximum neutron star masses < 2M$_\odot$**

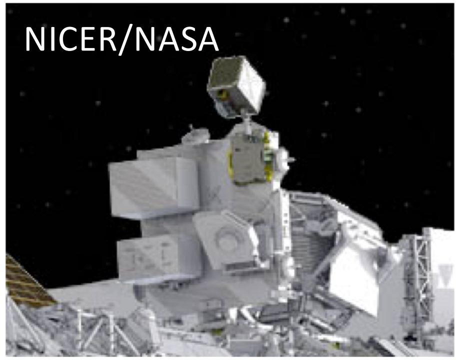
Solution?

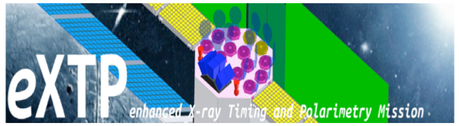
- stiffer YN and YY interactions
- hyperonic 3-body forces
- push of Y onset by Δ-isobars or meson condensates
- quark matter below Y onset
- dark matter, modified gravity theories…

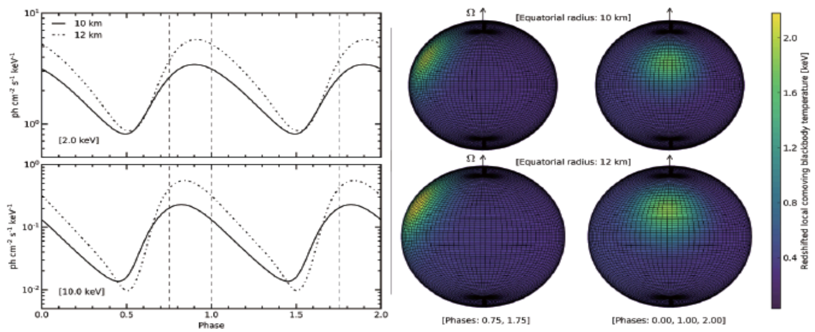
Future: space missions to study the interior of NS

Watts et al. '19



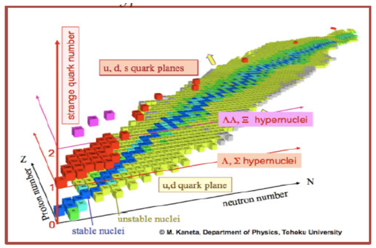




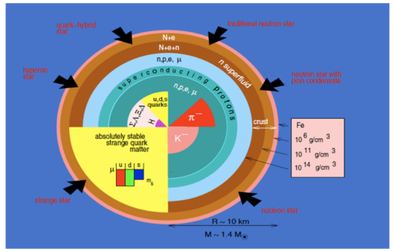


Constraints from pulse profile modelling of rotation-powered pulsars with eXTP

and multimessenger astronomy



Present and Future



A lot of experimental, observational and theoretical effort has been invested to understand hyperons in nuclei and neutron stars

Hyperon-nucleon and hyperon-hyperon interactions are crucial for hypernuclear physics and the physics of compact objects, such as neutron stars

Neutron stars provide a unique scenario for testing hyperons at extreme densities

The future of hyperon physics relies on particle and nuclear experiments as well as X-ray and multimessenger astronomy

THOR
STRONG 2020
PHAROS THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS
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