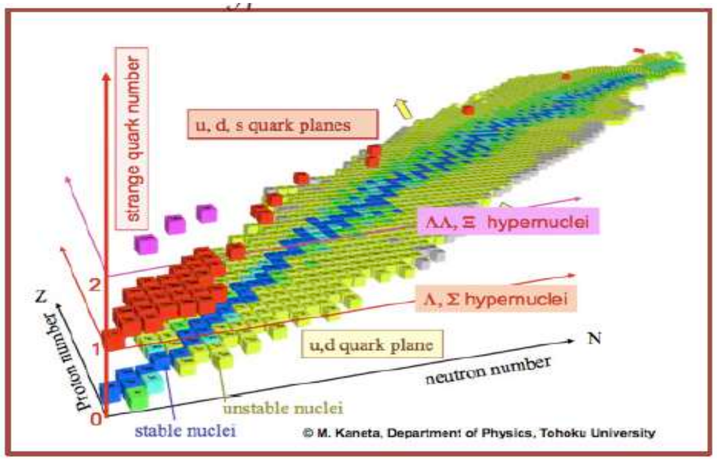
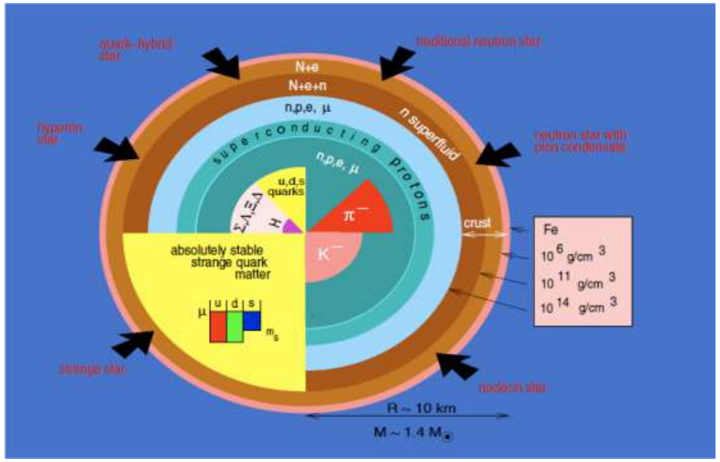


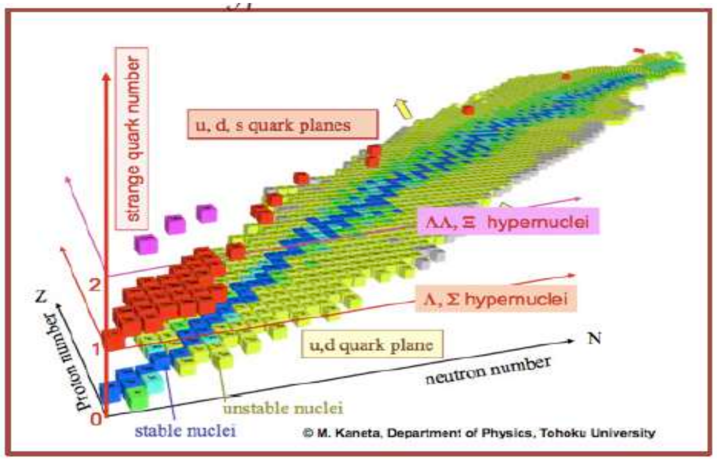


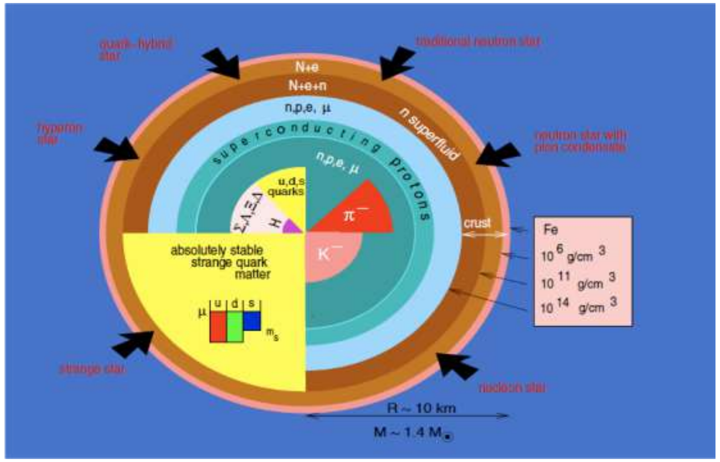
Strangeness in Nuclei and Neutron Stars

Laura Tolós

Institute of Space Sciences
CSIC IEEC

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





~~Strangeness~~ Hyperons in Nuclei and Neutron Stars

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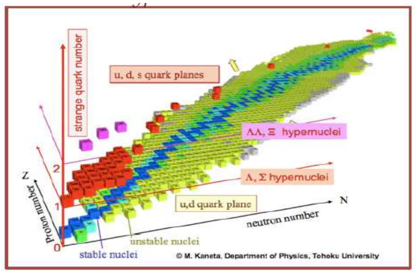
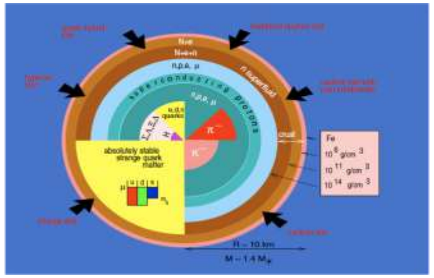


Outline

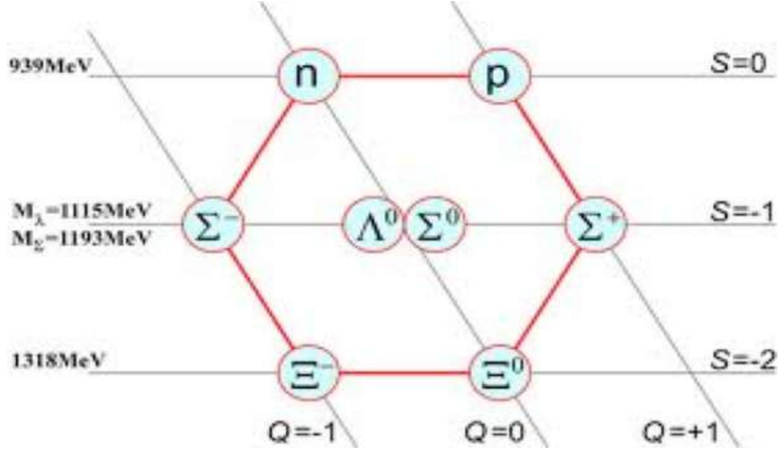


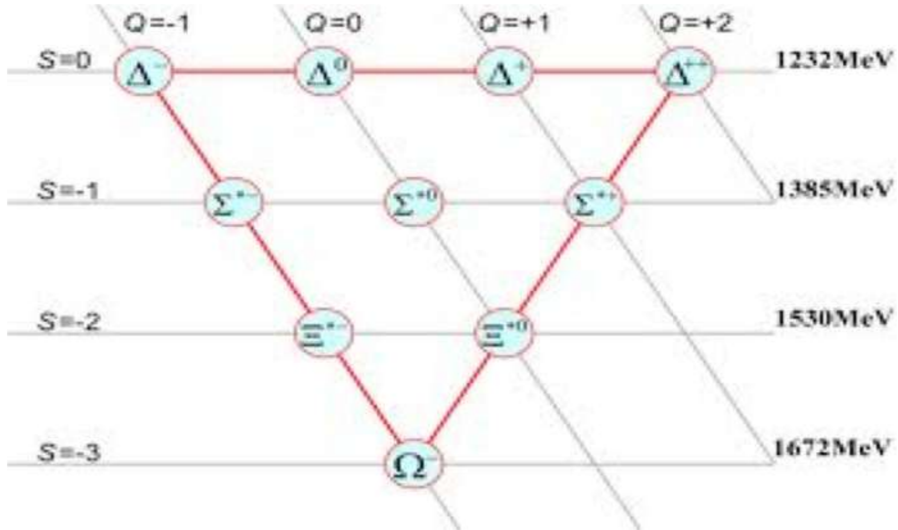
- Hyperons and where to find them
- YN and YY interactions
- Hypernuclei
- Hyperons in matter
- Hyperons and Neutron Stars
- Present and Future

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

A hyperon is a baryon containing one or more strange quarks

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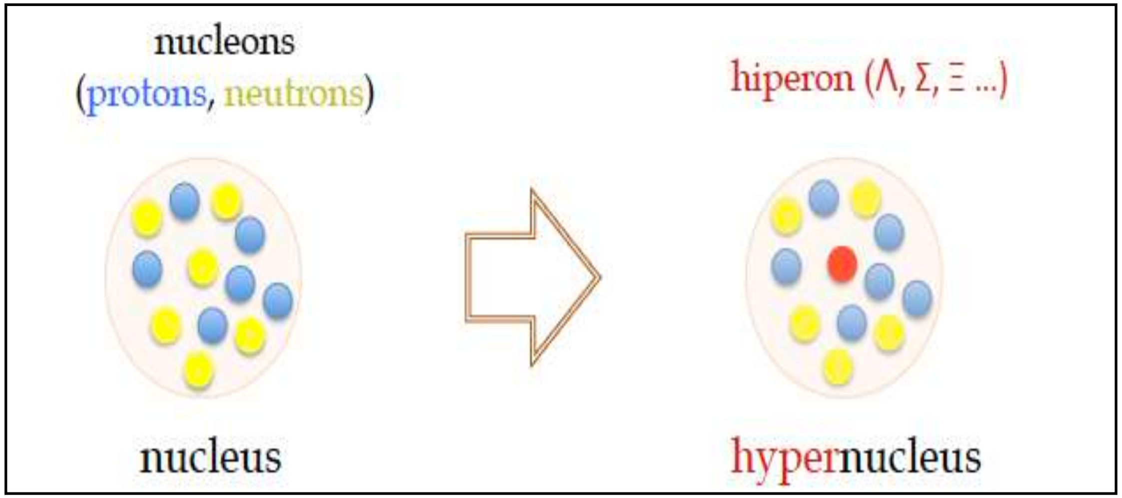
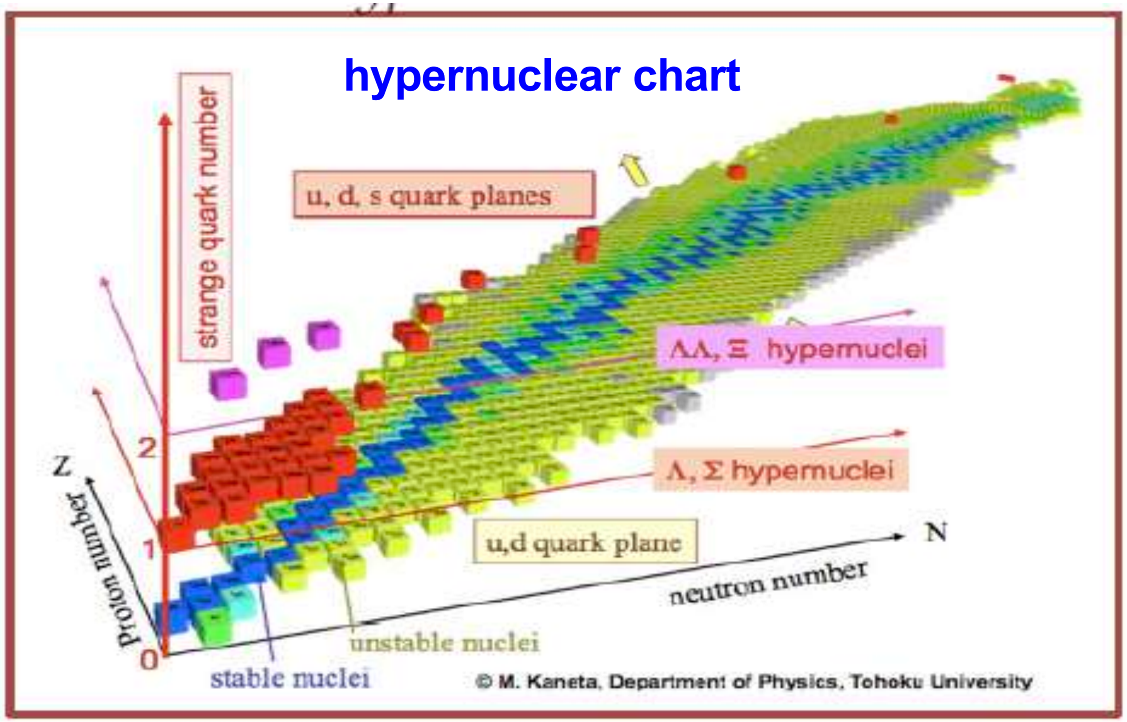


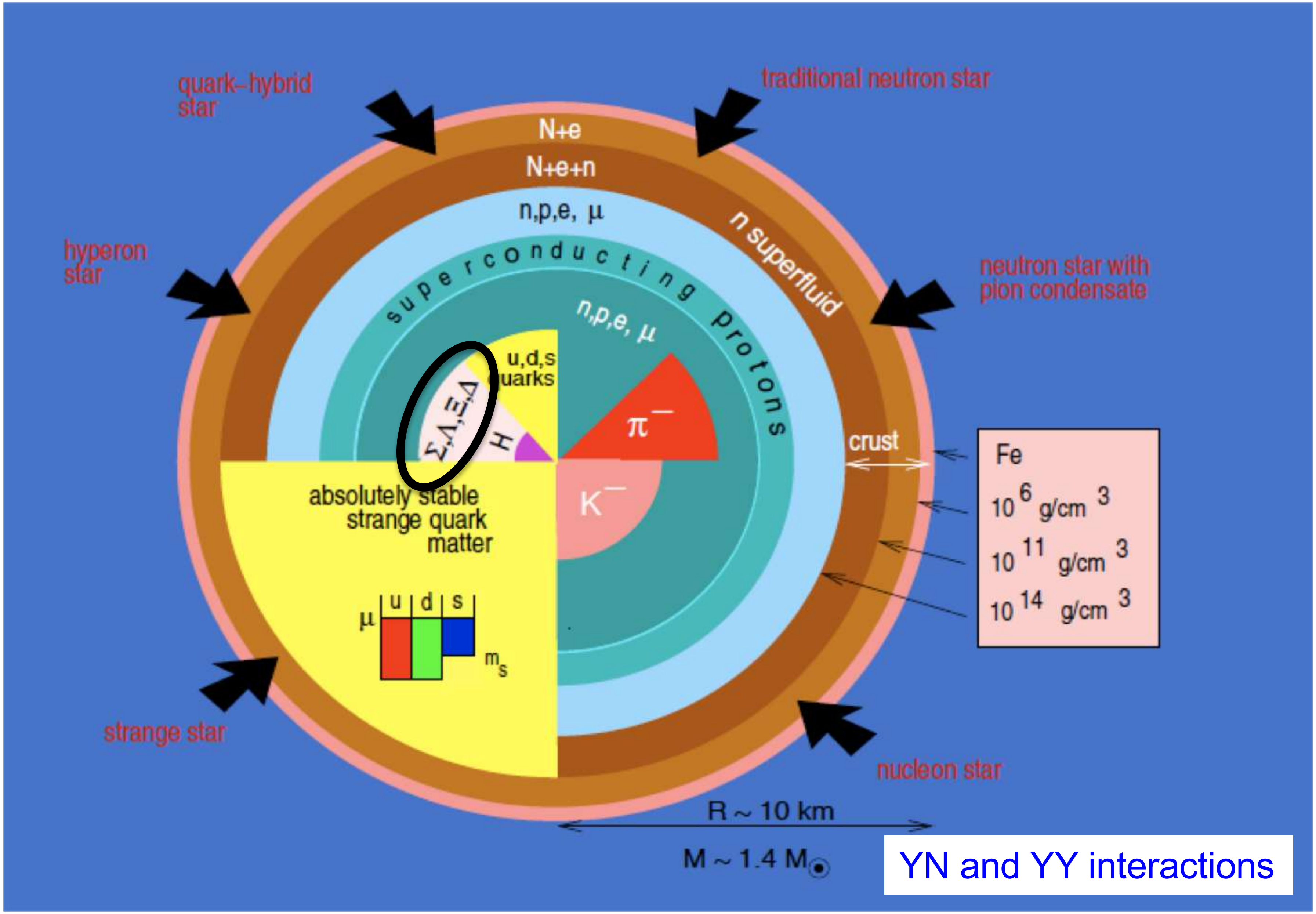
credit: A. Parreno

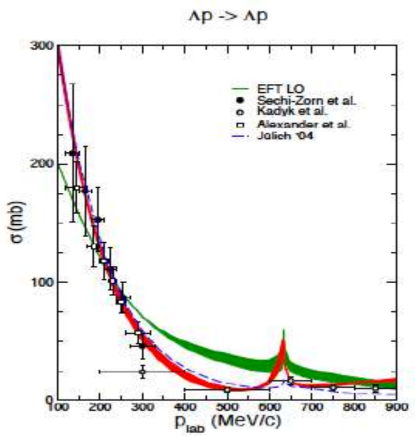


The study of hypernucleus allows for

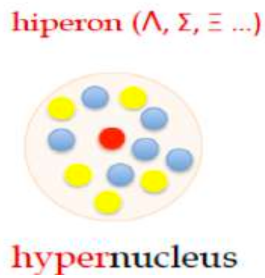
- new spectroscopy
- information on strong and weak interactions between hyperons and nucleons

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 ΛΛ- hypernuclei ($\Lambda\Lambda$ weak attraction)
- few Ξ-hypernuclei (ΞN attractive)
- no evidence of 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

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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

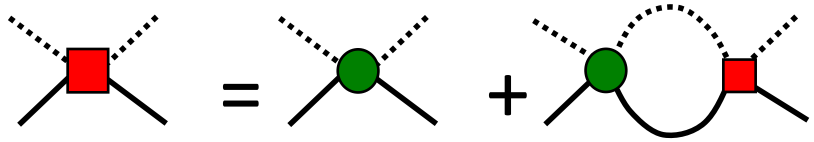
✓ Momentum Space, Full Energy Dependence & Non-localities

✓ Exchange of single mesons and higher order processes

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

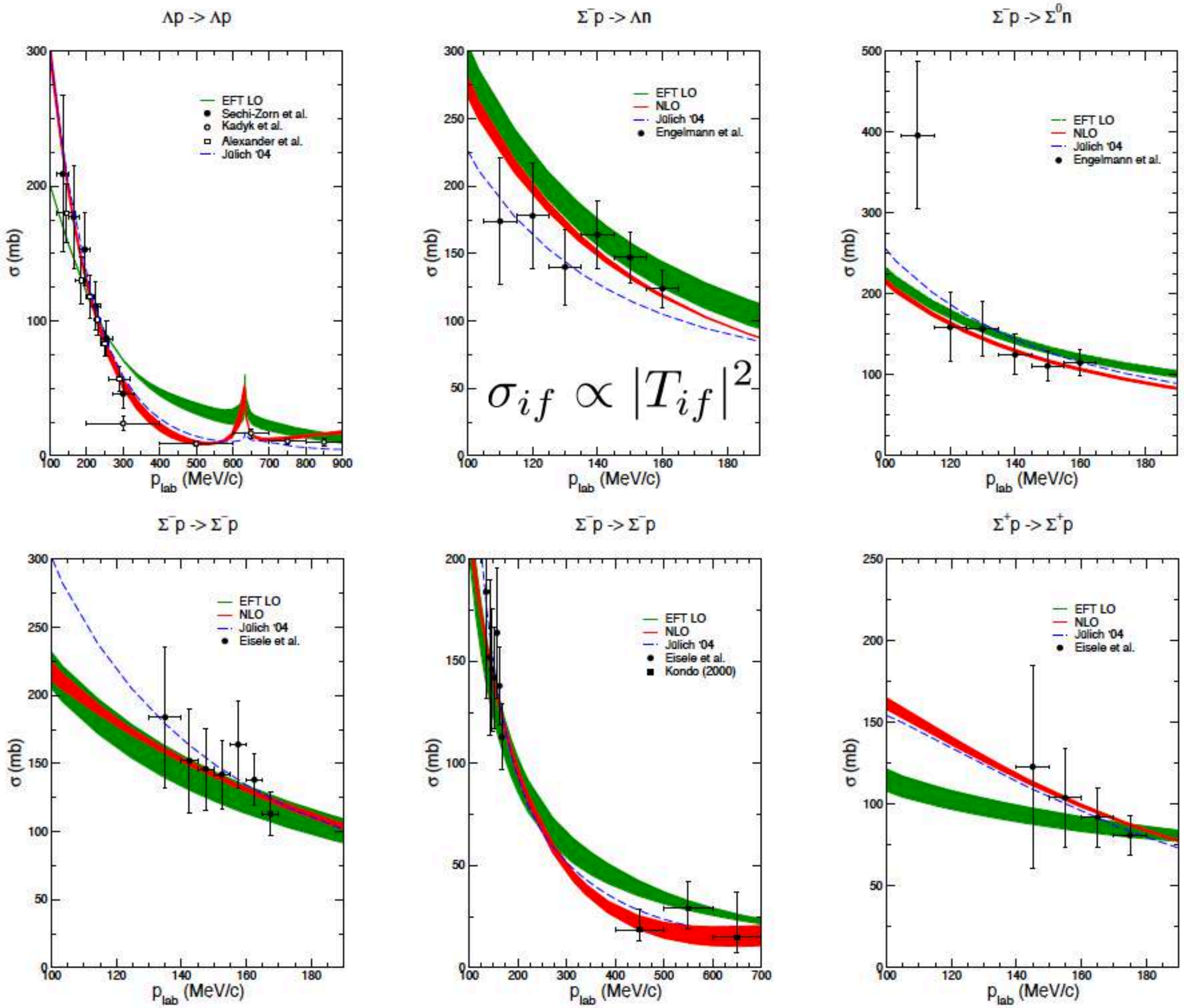
✓ Dipolar form factors

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

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

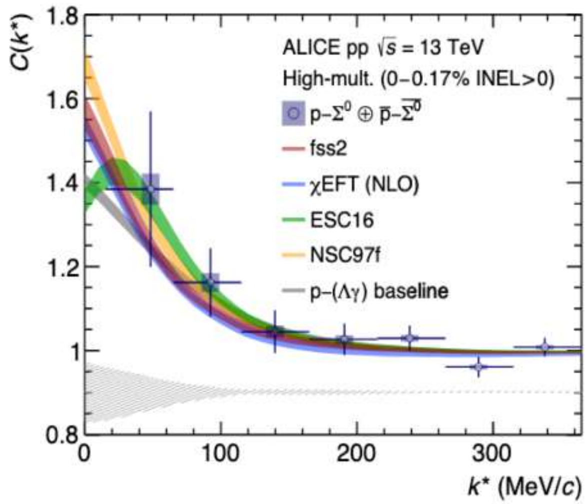


$$\sigma_{if} \propto |T_{if}|^2$$

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

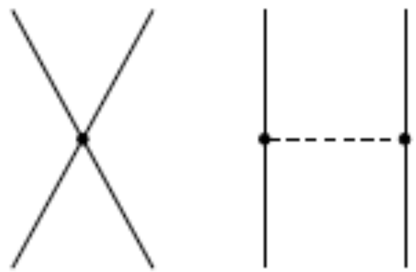
Baryon-Baryon interaction in SU(3) χEFT **a la Weinberg** (1990);

- **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 :

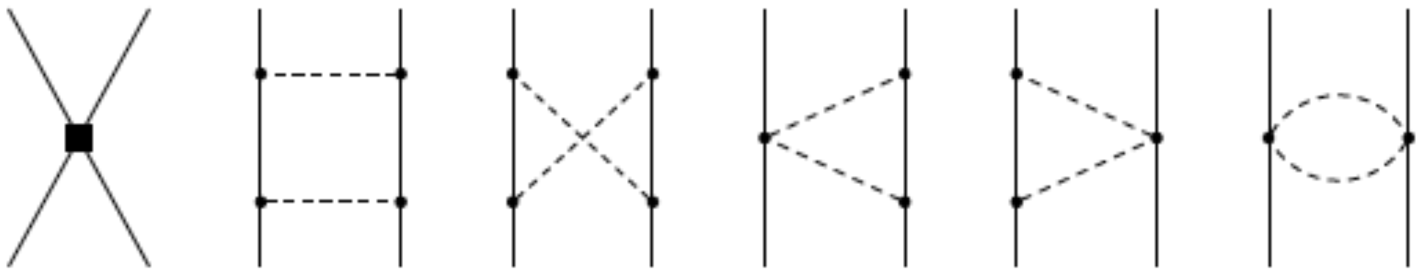


$$\nu = 2 - B + 2L + \sum_i v_i \Delta_i \ ,$$

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

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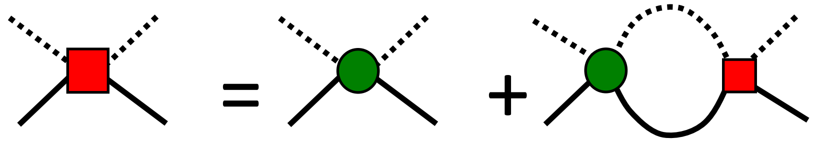
NLO: J.H., N. Kaiser, U.-G. Meißner, A. Nogga, S. Petschauer, W. Weise, NPA 915 (2013) 24

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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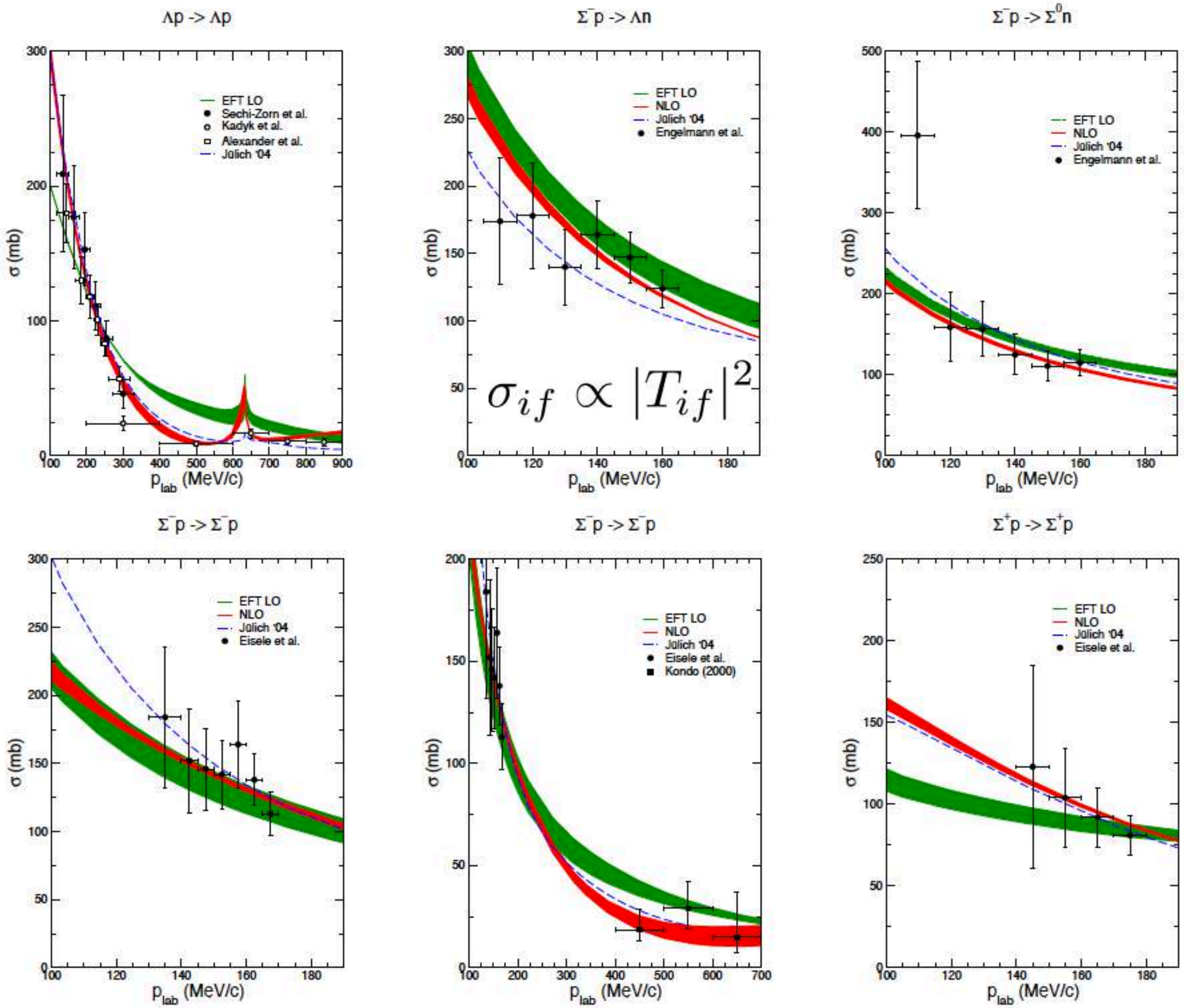

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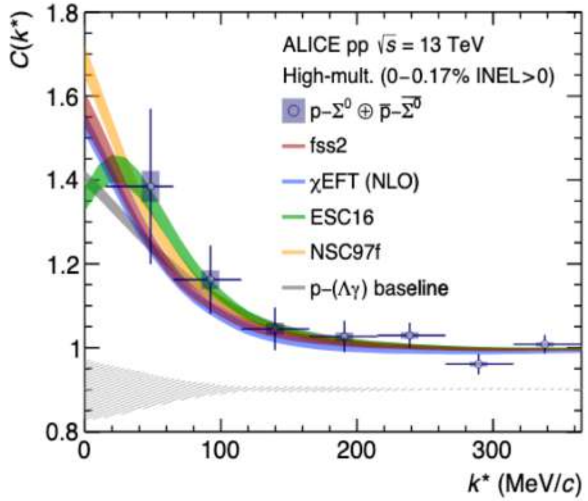
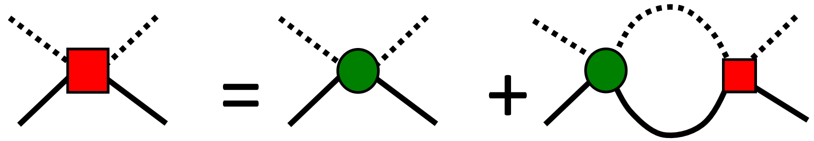
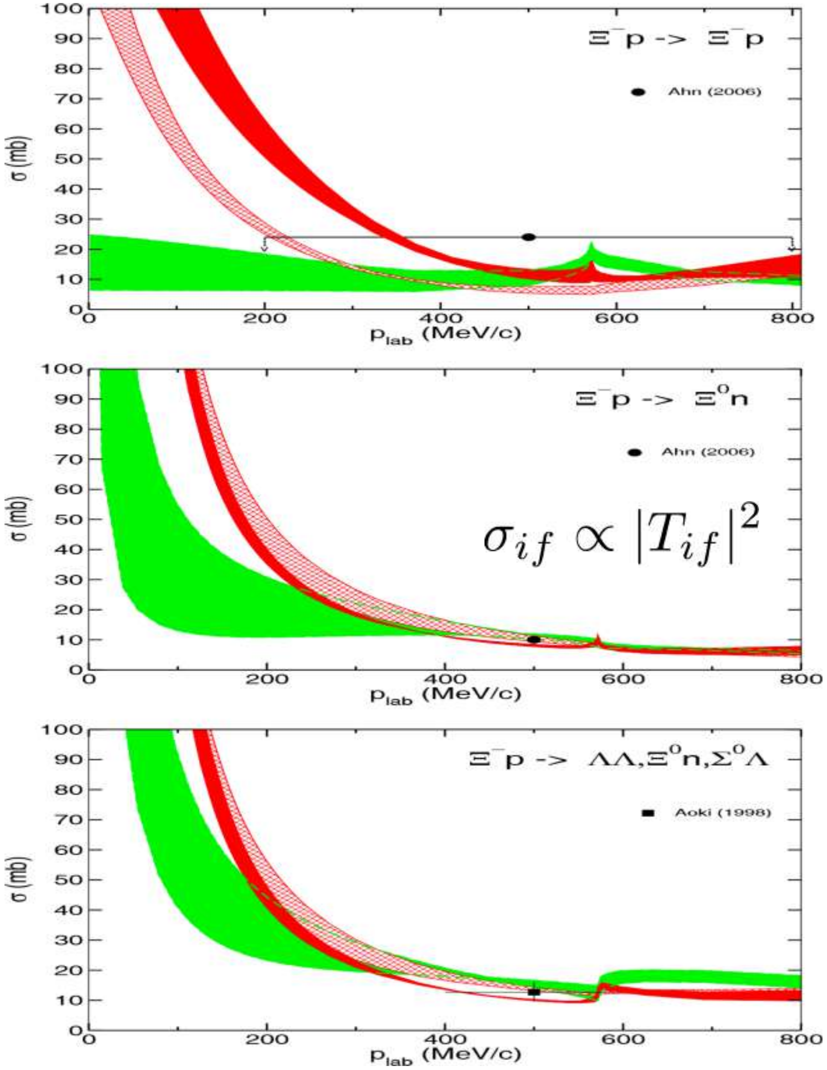


S. Acharya et al. 2019

ΞN scattering



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

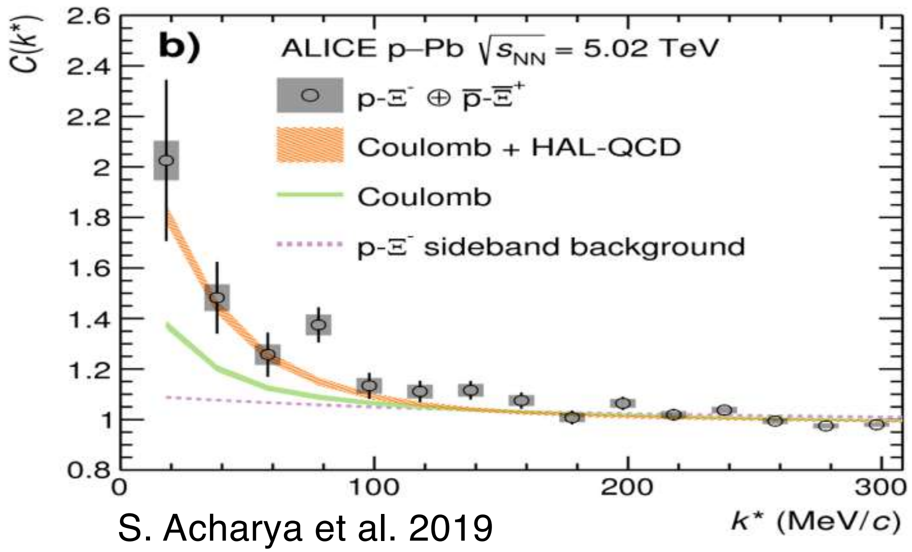


$$\sigma_{if} \propto |T_{if}|^2$$

ΞN cross sections are small

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

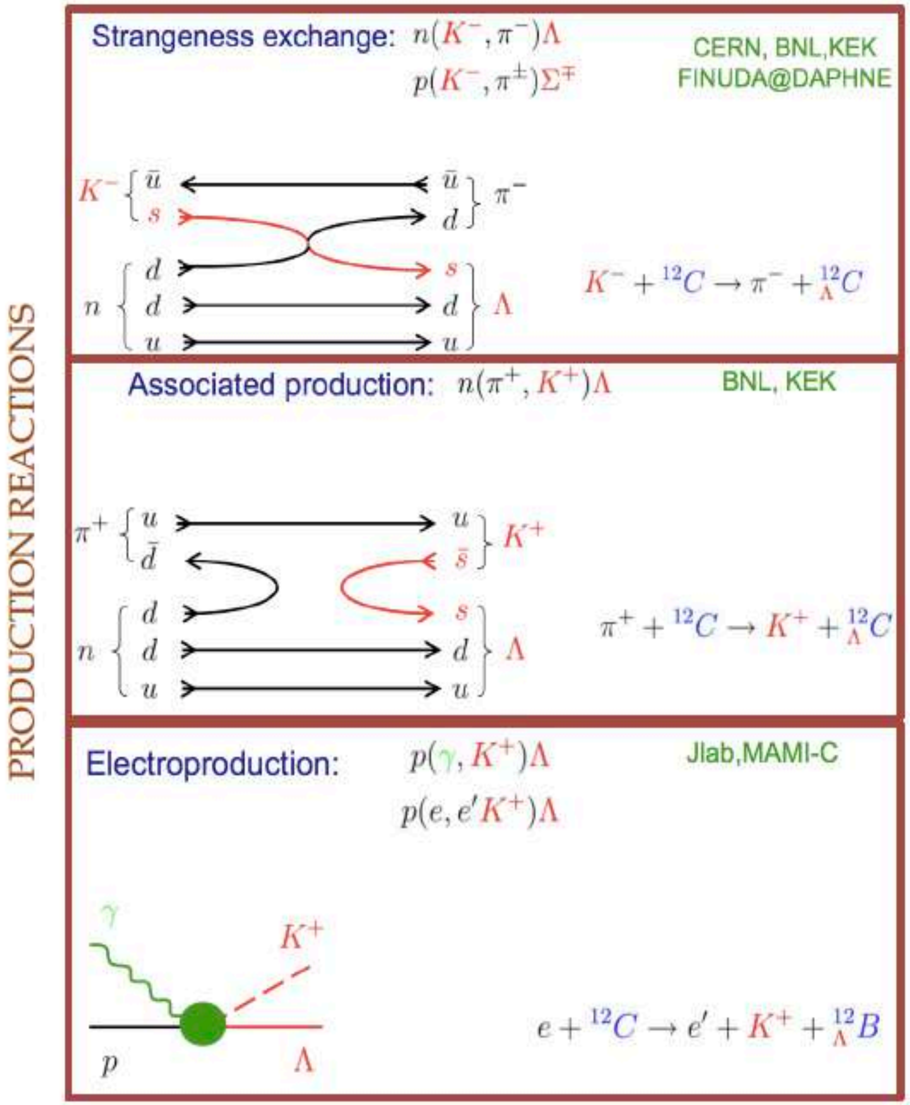
Scarce experimental information.
New results from femtoscopy



S. Acharya et al. 2019

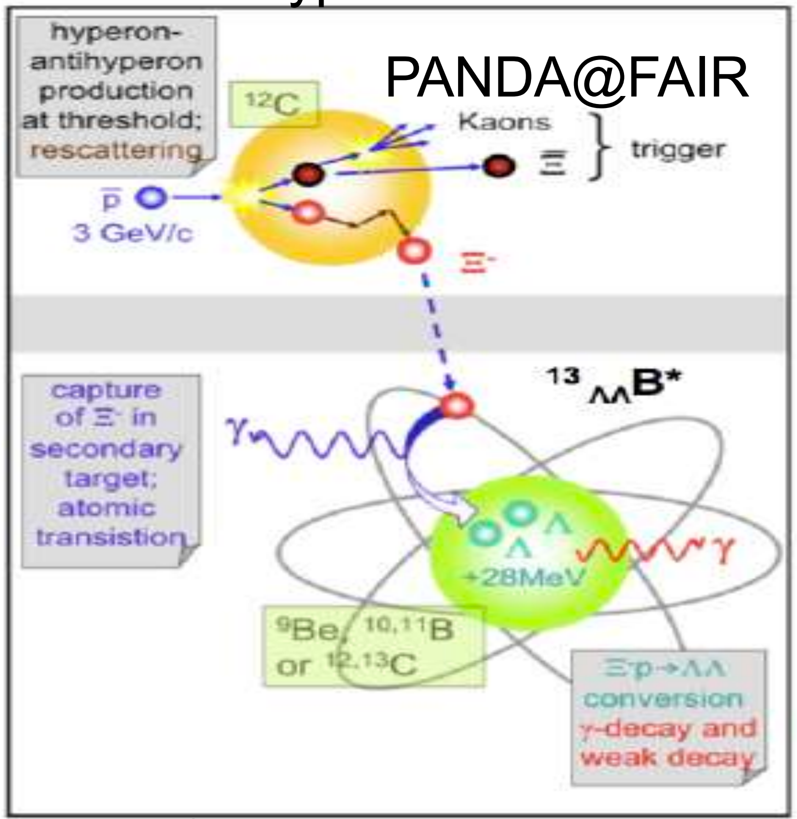
Hypernuclei

Λ hypernuclei



credit: A. Parreno

Double Λ hypernuclei



credit: A. Sanchez-Lorente

Also Ξ hypernuclei @ BNL, KEK

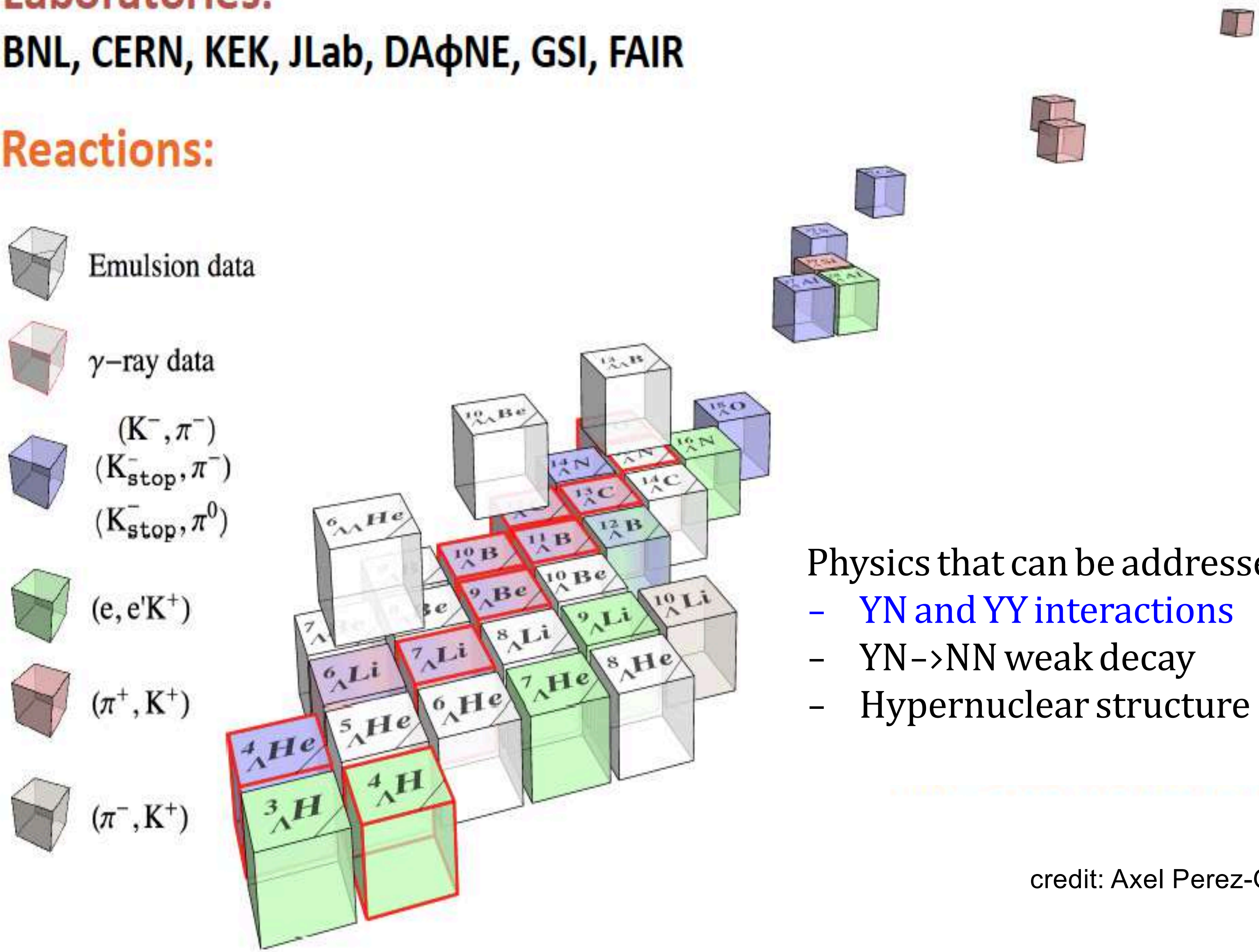
$$^{12}C(K^-,K^+)^{12}_{\Xi^-}Be$$

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

Laboratories:

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

Reactions:

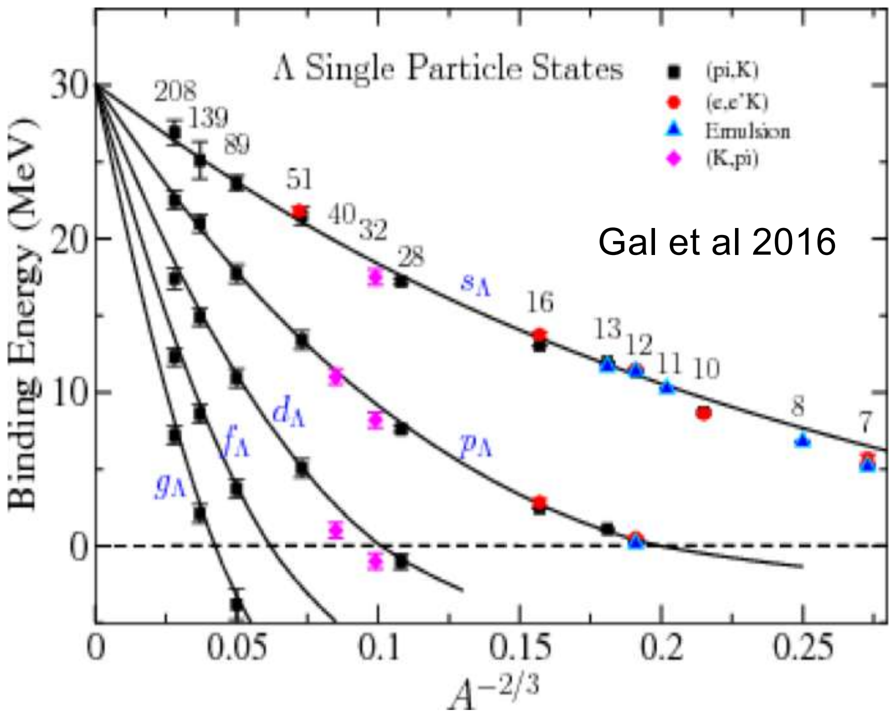


Physics that can be addressed：

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

credit: Axel Perez-Obiol

Binding energy of Λ hypernuclei

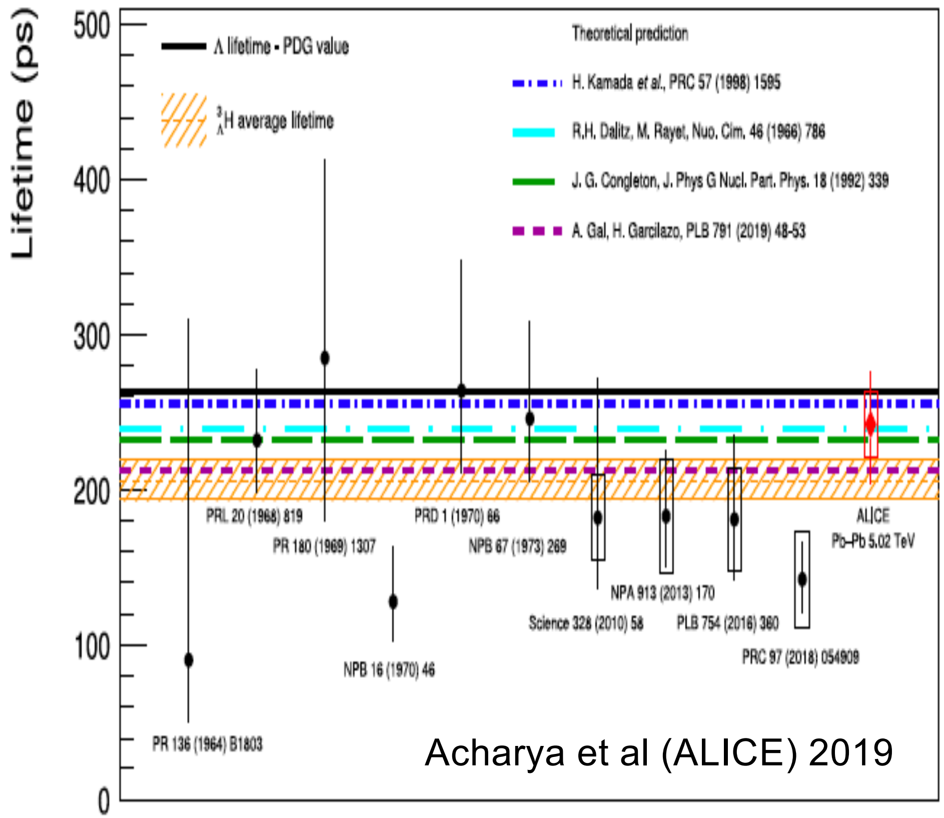


Binding energy of different hypernuclei as function of the mass number

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



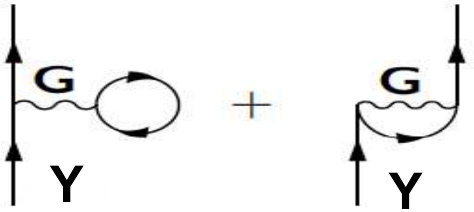
Expected $\tau(^3_\Lambda H) = \tau(\Lambda)$

⇔ 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



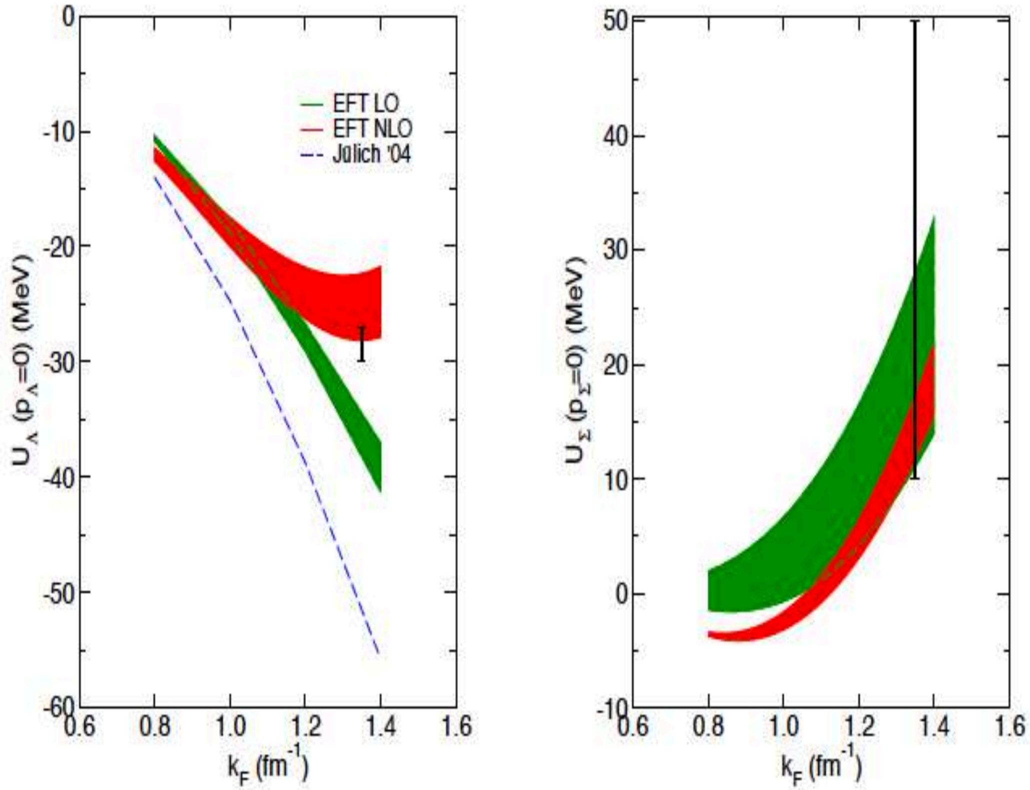
$$G = V + V\frac{Q_{\text{pauli}}}{E_0 - H_0}G$$

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

	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!



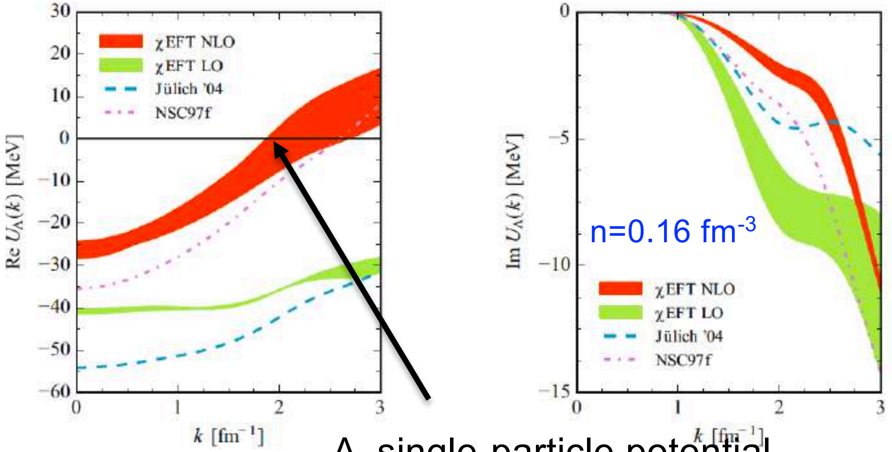
Haidenbauer and Meißner , NPA 936 (2015) 29

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

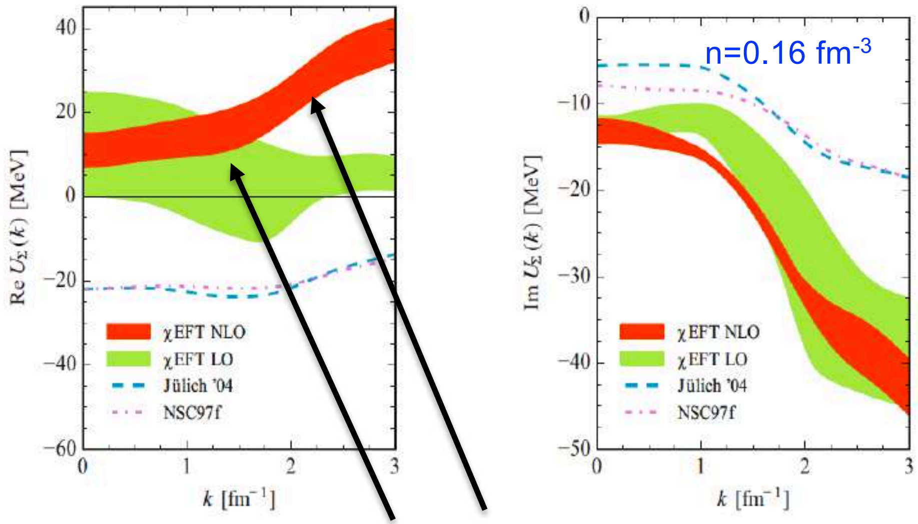
Improving on the calculation by using χEFT NN interaction and continuous choice in Brueckner-Hartree-Fock approach while investigating isospin-asymmetric matter

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

symmetric nuclear matter

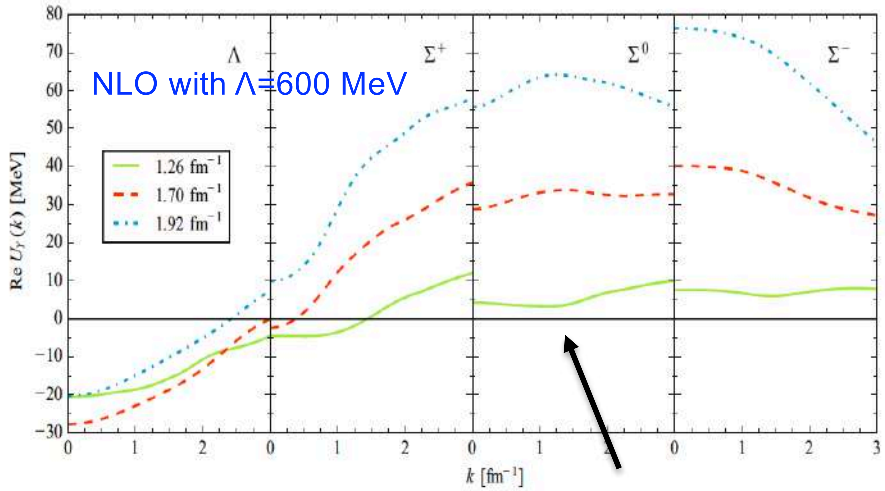


Λ single-particle potential at NLO turns repulsive k~2 fm^{-1}

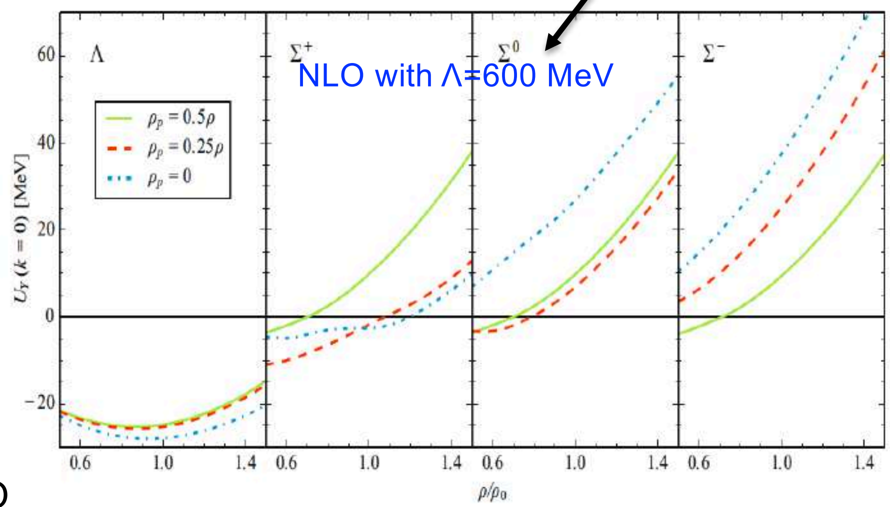


Σ-nuclear potential is moderately repulsive for LO and NLO

neutron matter

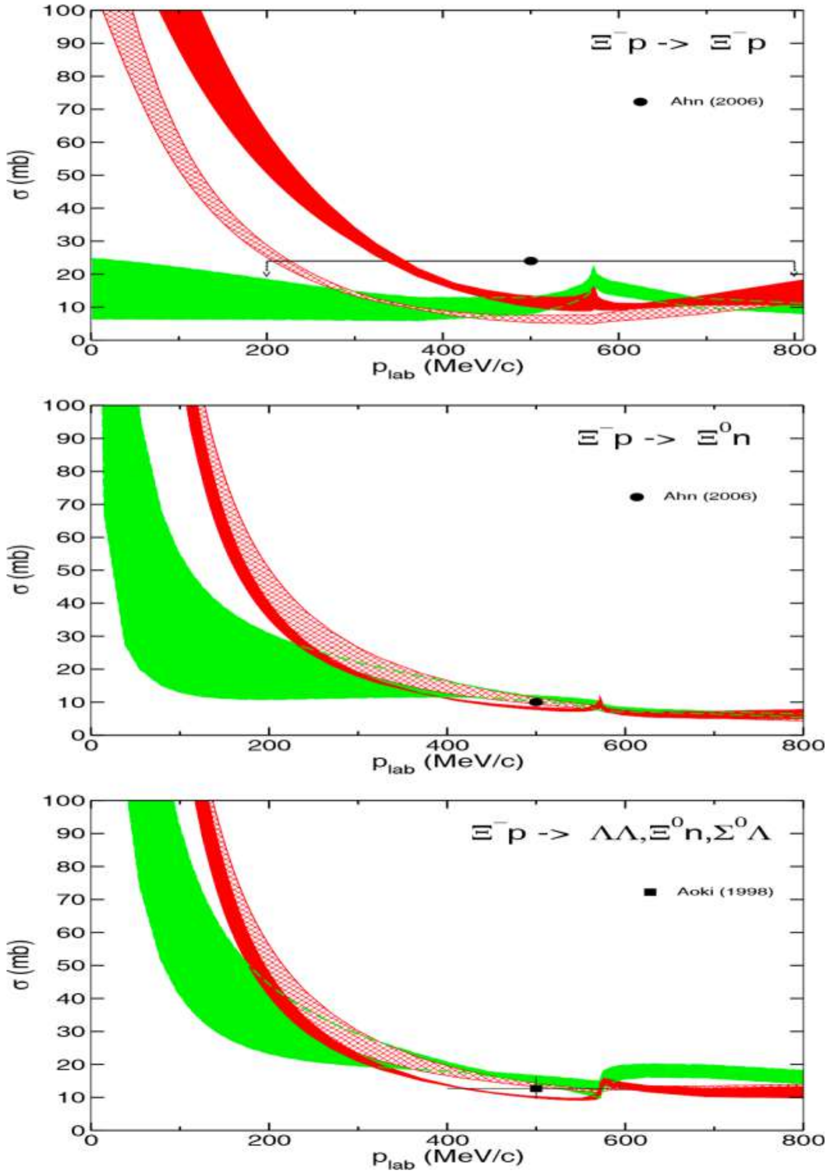


strong isospin dependence of the ΣN interaction



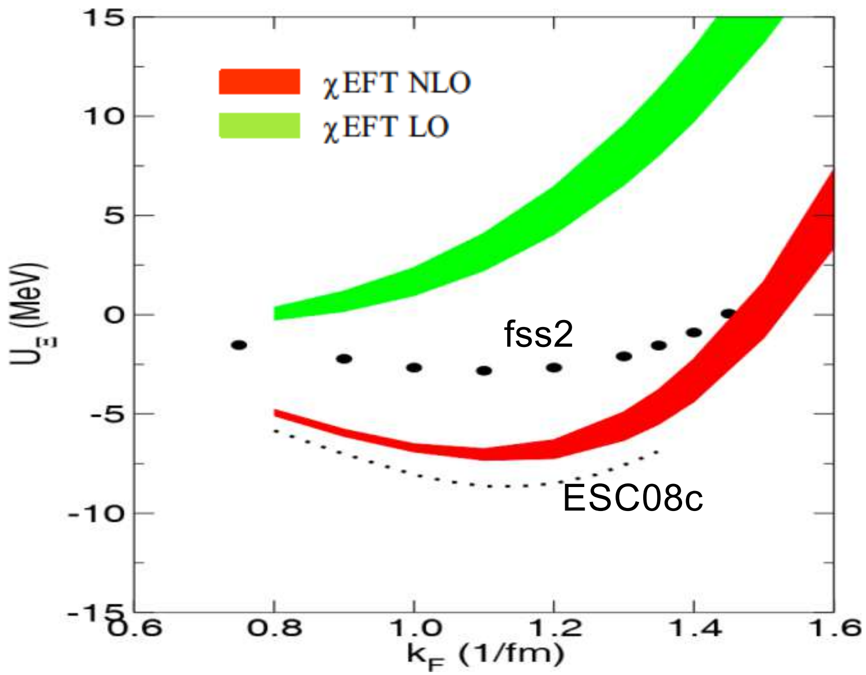
Ξ in dense matter

ΞN cross sections are small



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

Ξ in dense matter

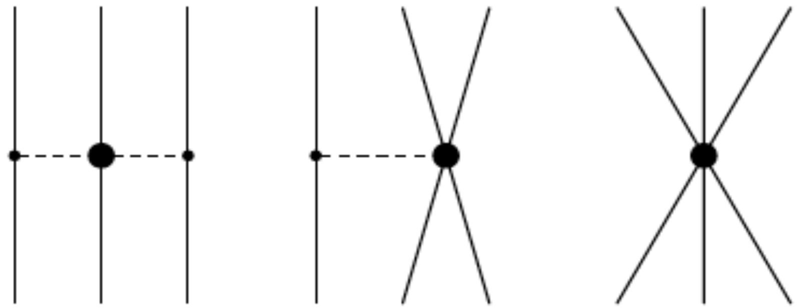


Moderately attractive Ξ-nuclear interaction, with $U_{\Xi}(0,k_{F0})$ ~ -3 to -5 MeV.
Smaller than $U_{\Xi}(n_0)$ ~-14 MeV Khaustov et al'00
and in line with other BHF studies with phenomenological ΞN potentials

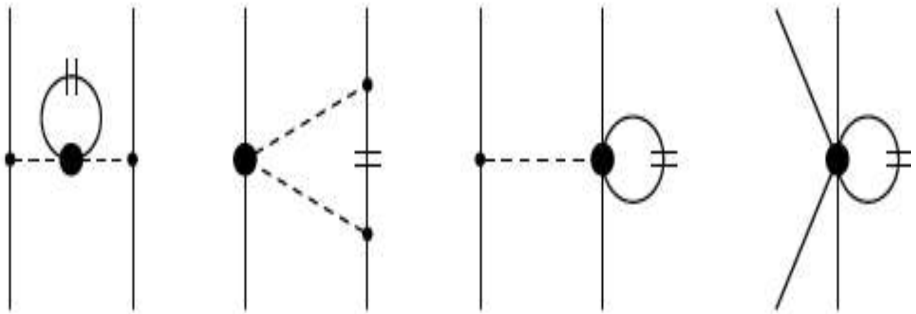
Λ in dense matter: including three-body forces

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 N^2LO)



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



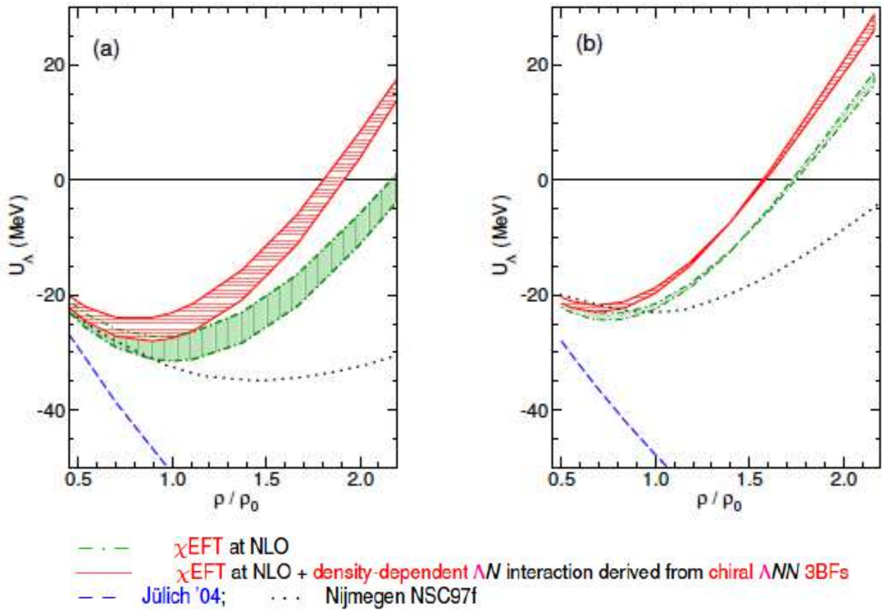
closing two baryon lines summing over the Fermi sea

credit: Haidenbauer

Λ in dense matter

symmetric matter

neutron matter



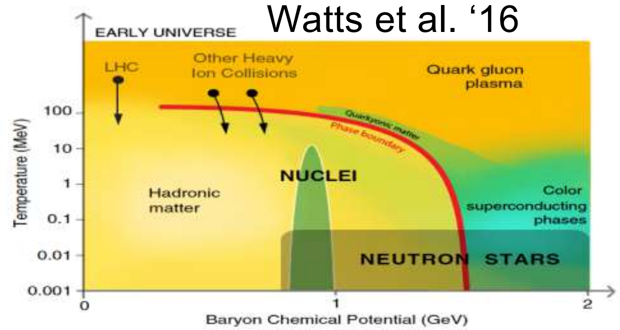
χEFT gives little attraction or even repulsion for $n > n_0$

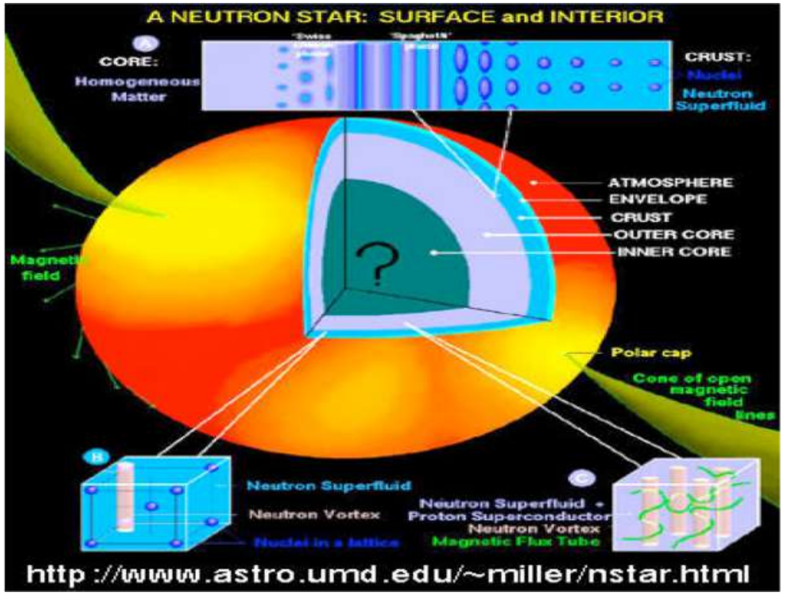
In neutron stars, hyperons will appear at high density!!

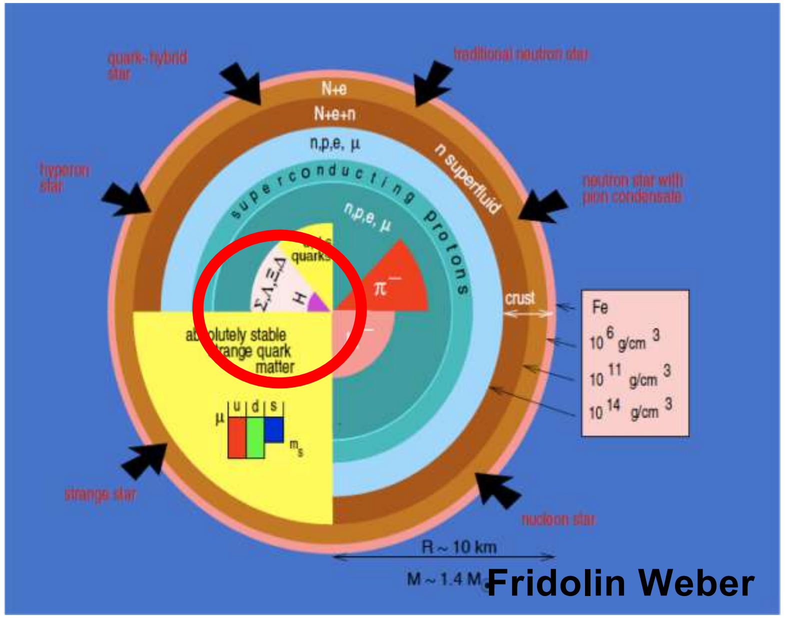
Solution of the Hyperon Puzzle?

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 5-10 ρ_0 ($n_0 = 0.16\ \text{fm}^{-3} \Rightarrow \rho_0 = 3 \cdot 10^{14}\ \text{g/cm}^3$)

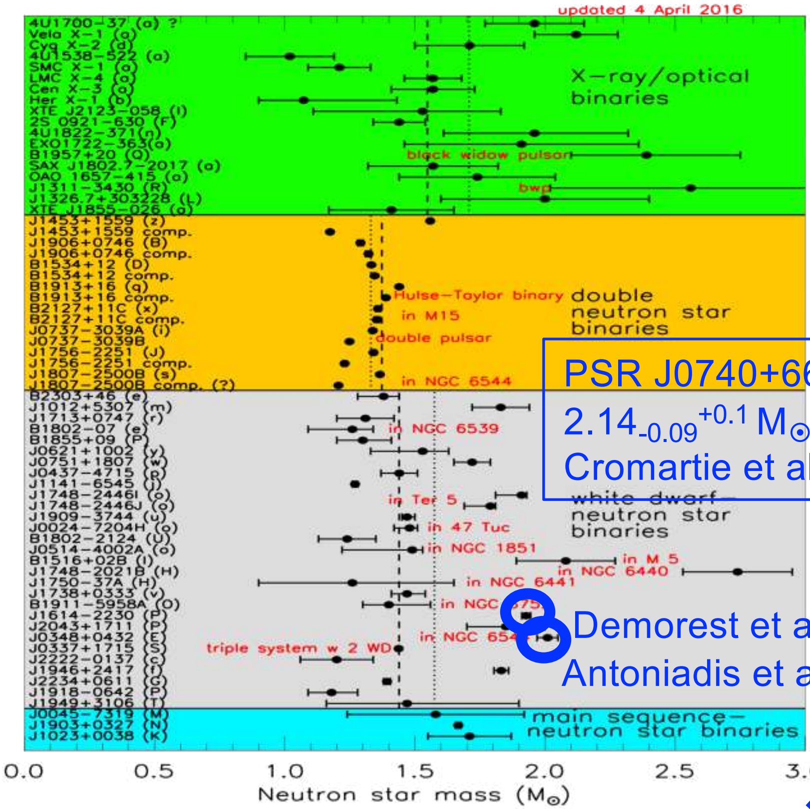
• magnetic field : $B \sim 10^{8..16}$ G

• temperature: $T \sim 10^{6...11}$ K

• observations: masses, radius (?), gravitational waves, cooling…

Masses

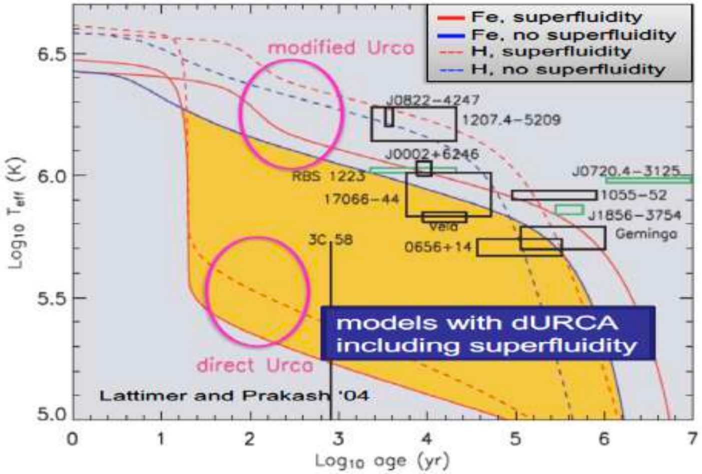
Lattimer '16



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

& Demorest et al '10
Antoniadis et al '13

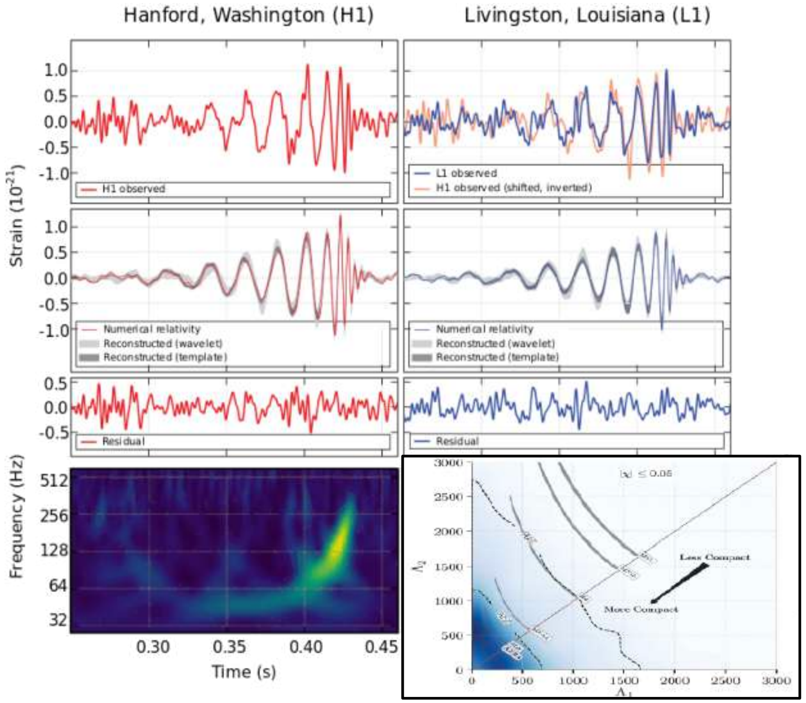
Cooling



Observations

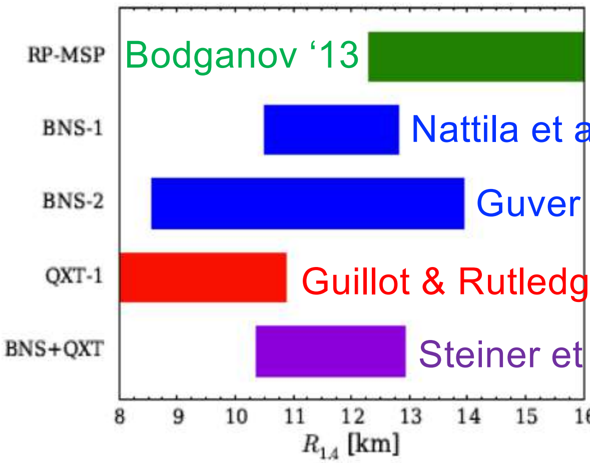
GW170817

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



Radius

Fortin et al. '15



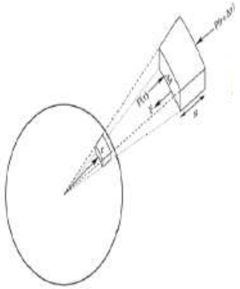
NICER
PSR J0030+0451

$R_{eq}=12.71_{-1.19}^{+1.14}$ 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

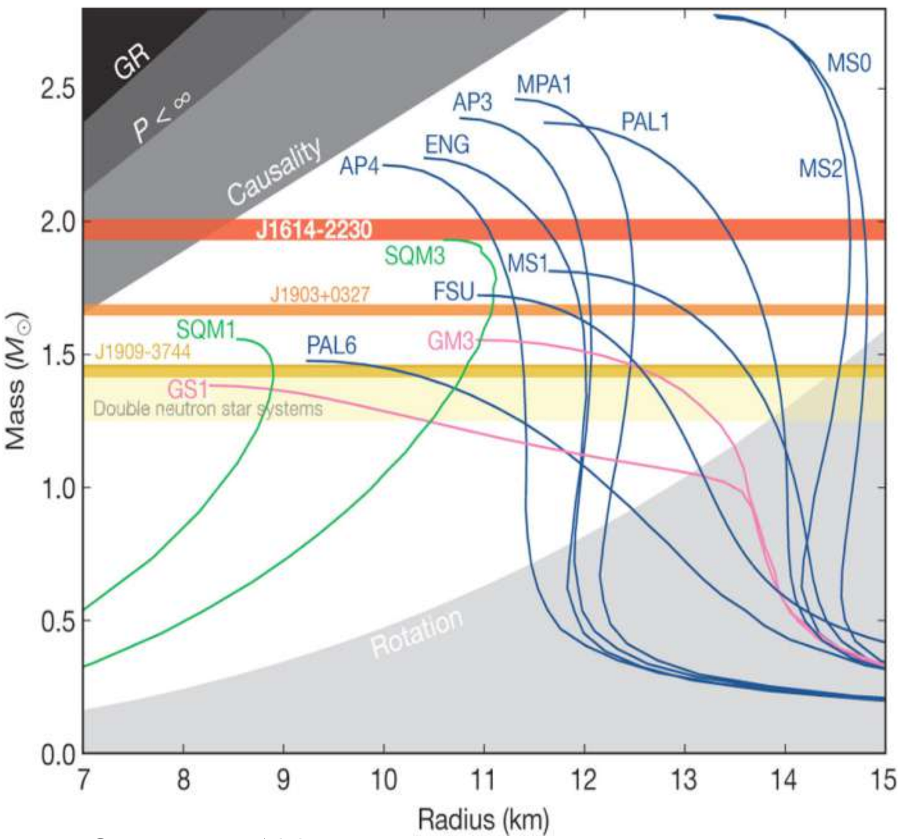
..also GW250419?

Mass-Radius Relation



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

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



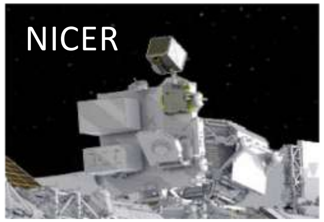
Ozel et al '16

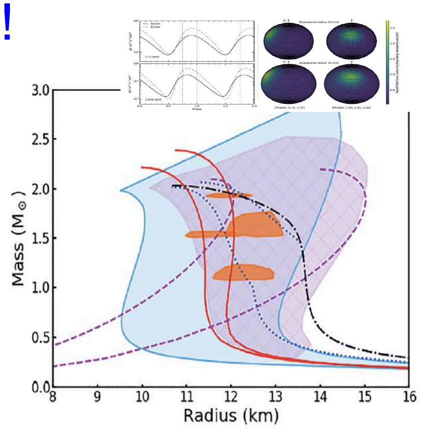
- primary ingredient:

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
    $R < (GM/2\pi)^{1/3}/\nu^{2/3}$

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

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

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

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

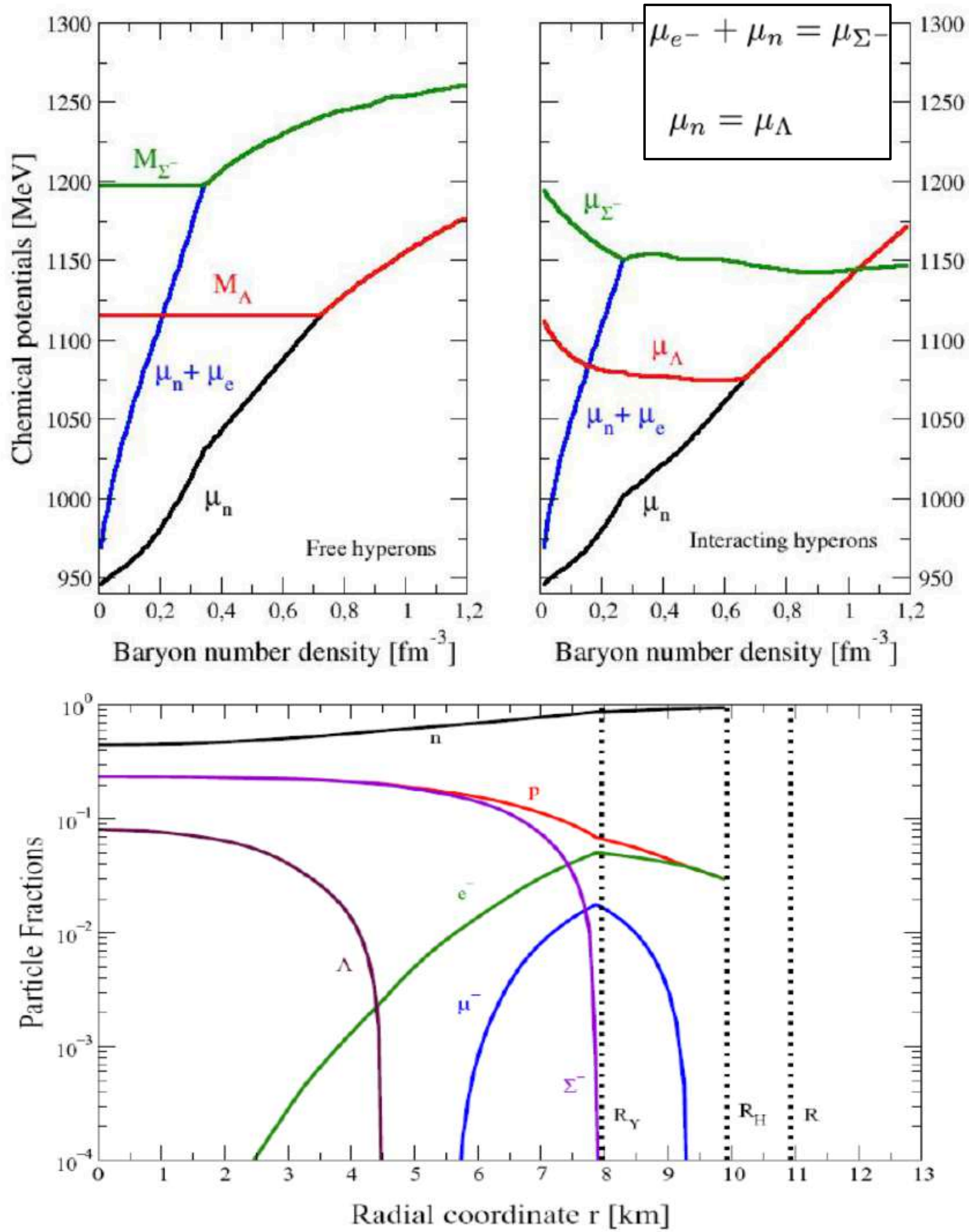
Hyperons might be present at $n \sim (2\text{-}3) n_0$!!!

β-stable hyperonic matter

μ_N is large enough to make N->Y favorable

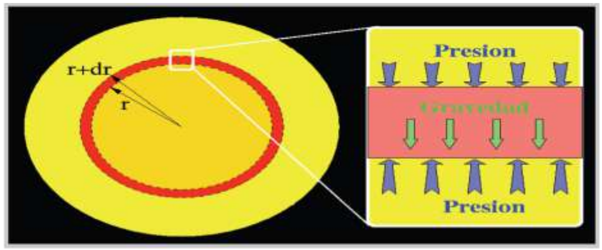
$$n + n \rightarrow n + \Lambda$$
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$
$$n + n \rightarrow p + \Sigma^-$$
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

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

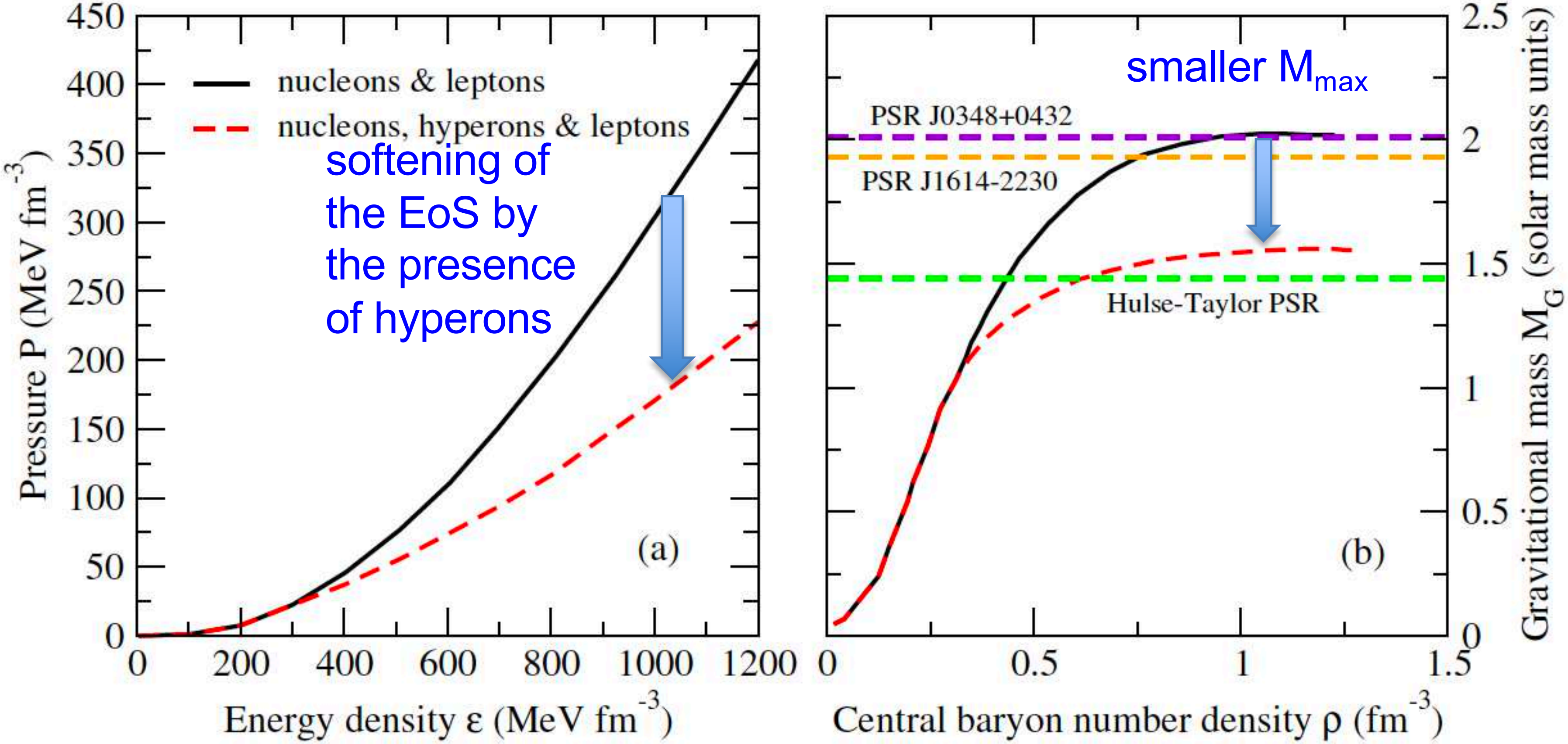


credit: Vidana

Inclusion of hyperons….



Credit:
Dani P. Page



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

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

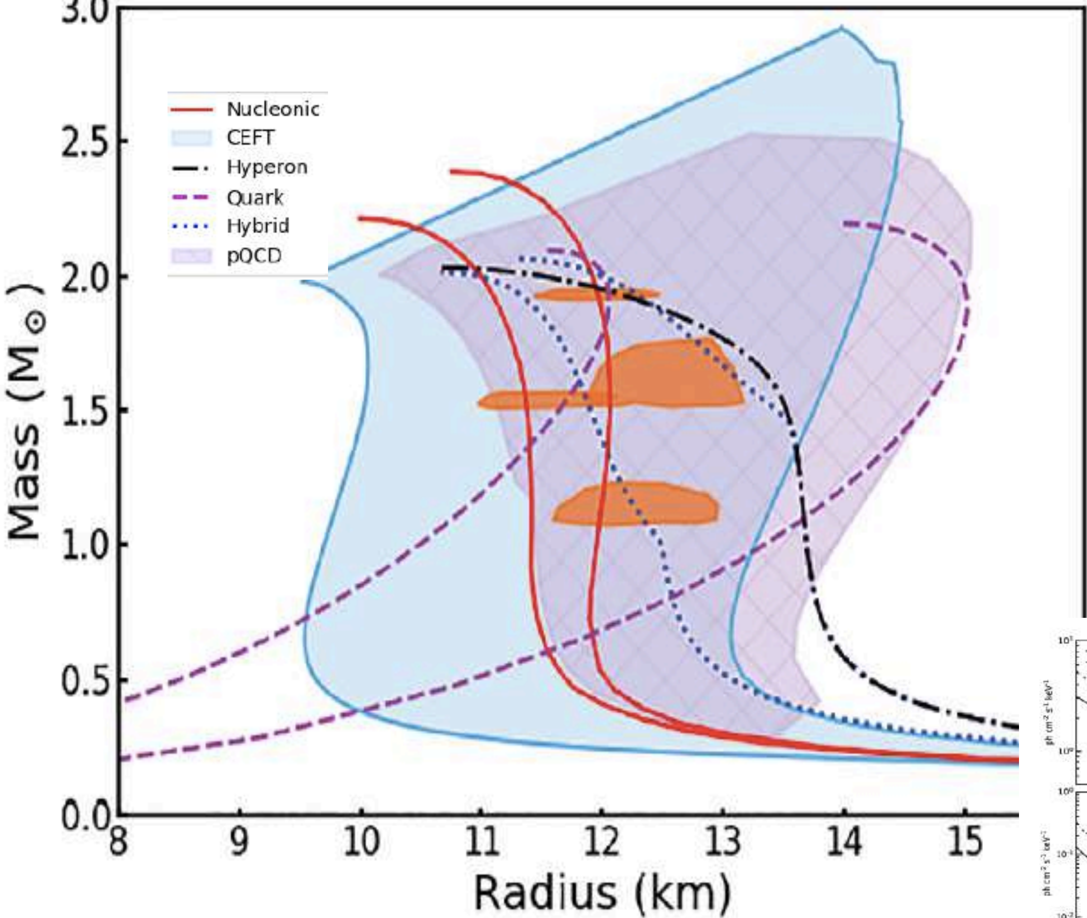
The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to **maximum neutron star masses < 2M$_\odot$**

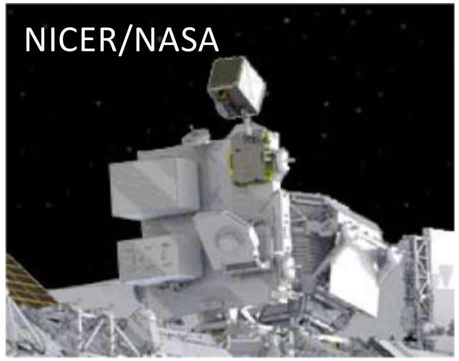
Solution?

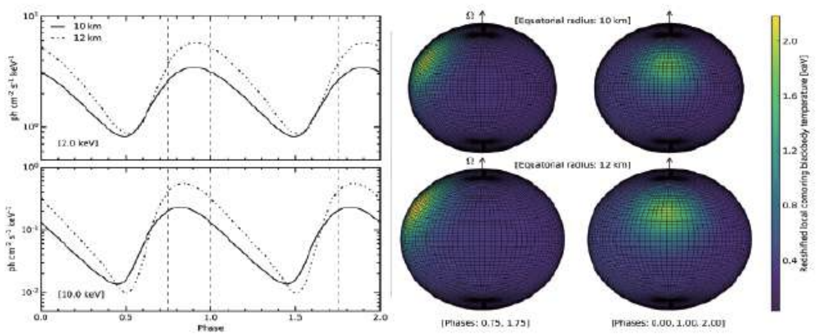
- stiffer YN and YY interactions
- hyperonic 3-body forces
- push of Y onset by Δ-isobars or meson condensates
- quark matter below Y onset
- dark matter, modified gravity theories…

Future: space missions to study the interior of NS

Watts et al. '19

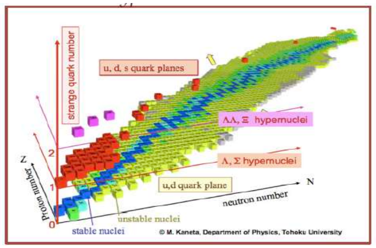




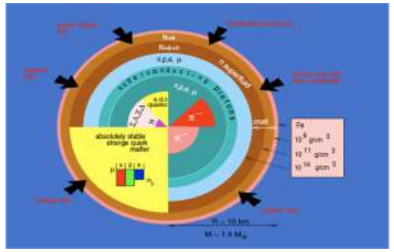


Constraints from pulse profile modelling of rotation-powered pulsars with eXTP

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 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