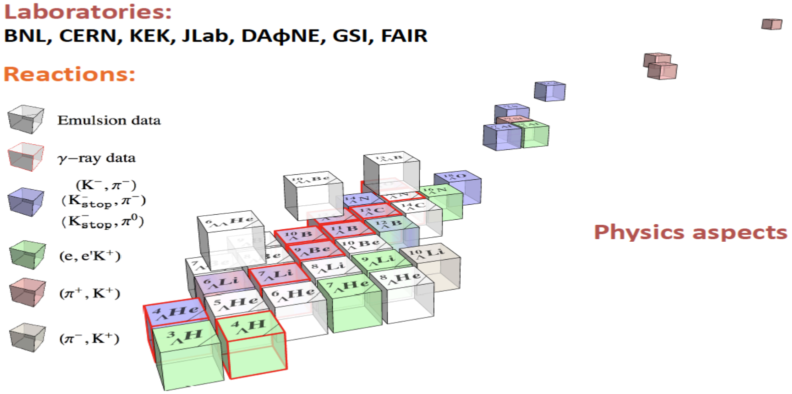
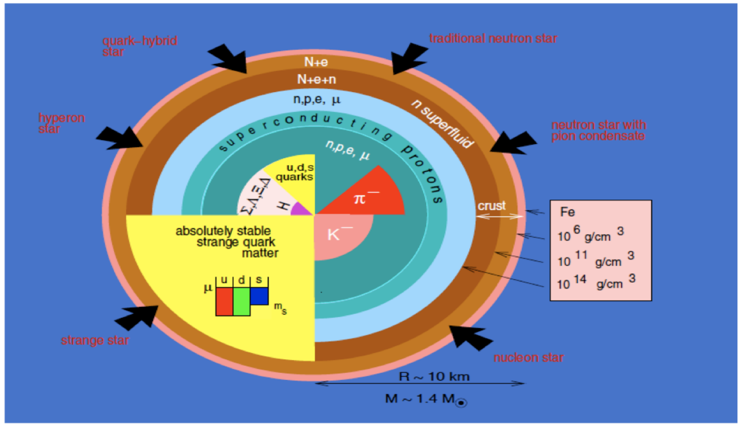
Laboratories:
BNL, CERN, KEK, JLab, DAΦNE, GSI, FAIR

Reactions:



Physics aspects



Strange Baryons in Nuclei and Neutron Stars

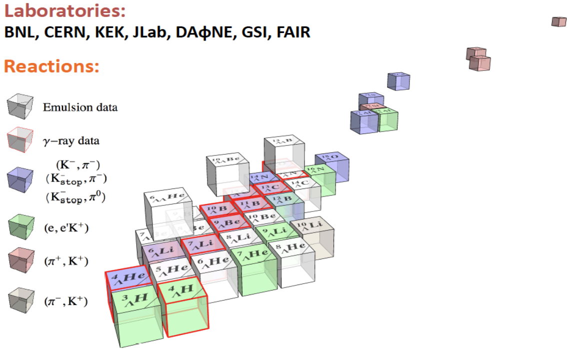
Institute of Space Sciences
CSIC IEEC
Consejo Superior de Investigaciones Científicas

Laura Tolós

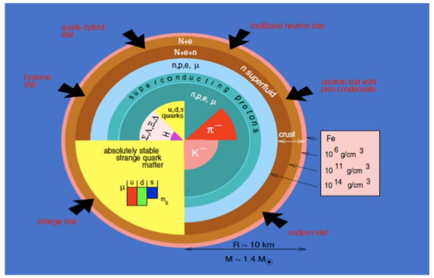
University of Stavanger

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

The 19th International Conference on Strangeness in Quark Matter
May 17-21, 2021, sponsored by Brookhaven National Laboratory, Upton, New York
SQM2021



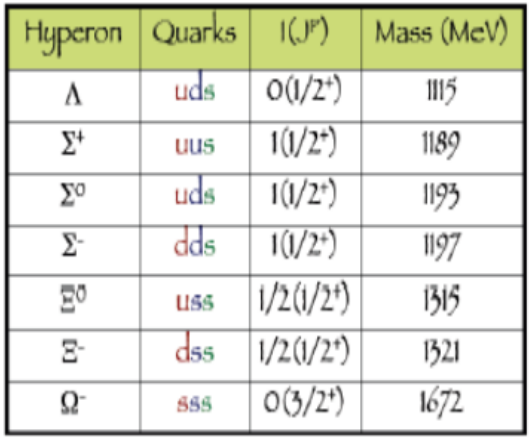
Outline



- 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



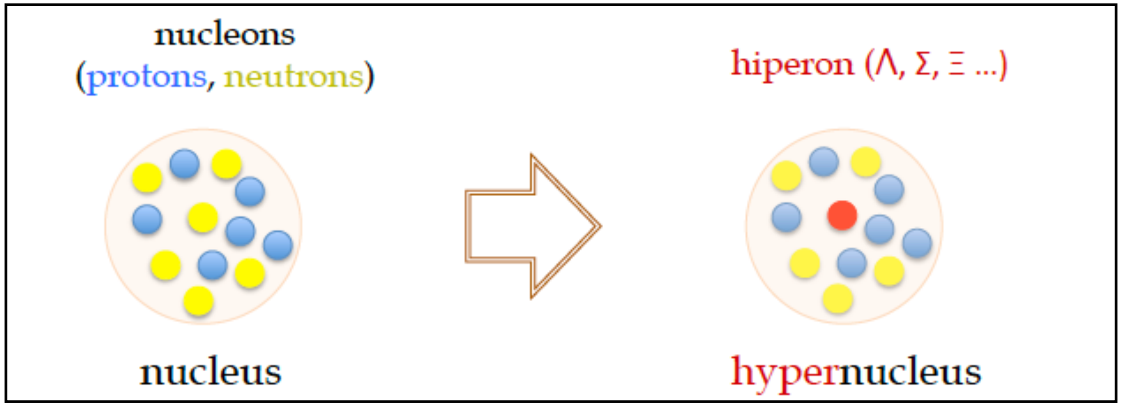
Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

credit: I. Vidana

The study of hypernucleus allows for

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

On Earth: Hypernuclei



credit: A. Parreno

Laboratories:
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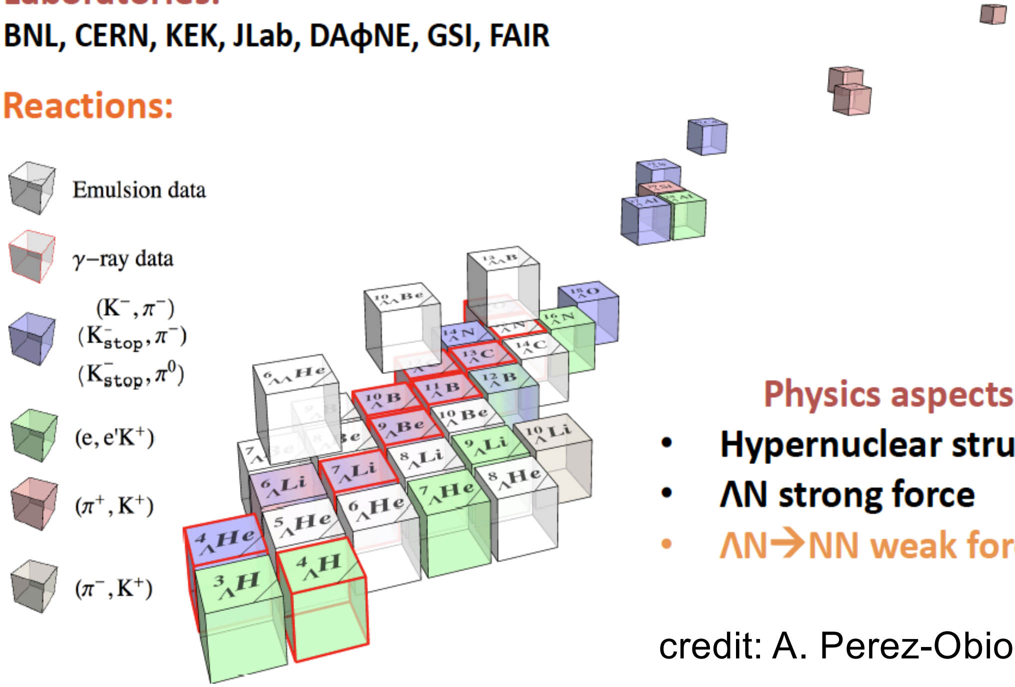
Reactions:

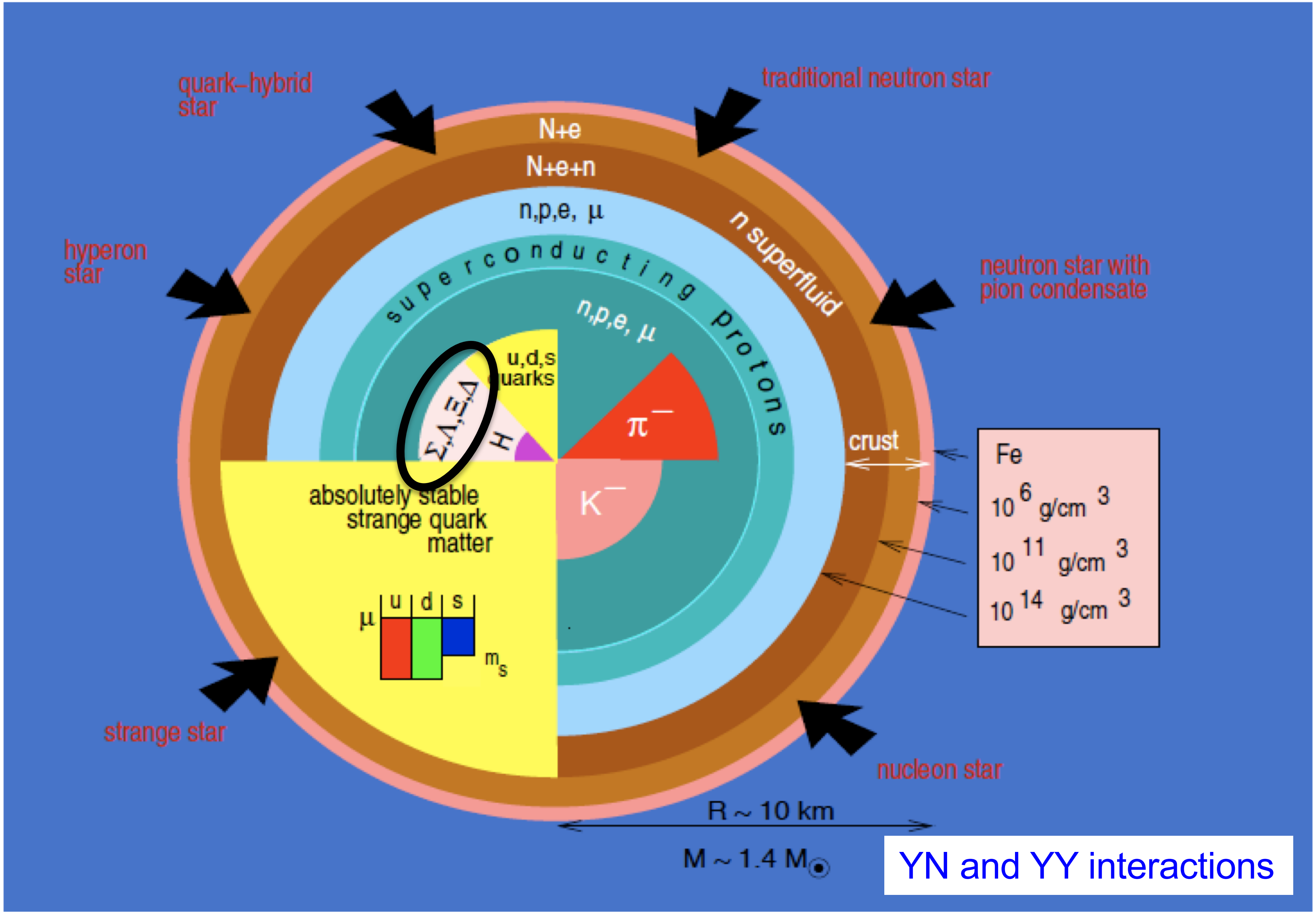


Physics aspects

- **Hypernuclear structure**
- **ΛN strong force**
- **ΛN→NN weak force**

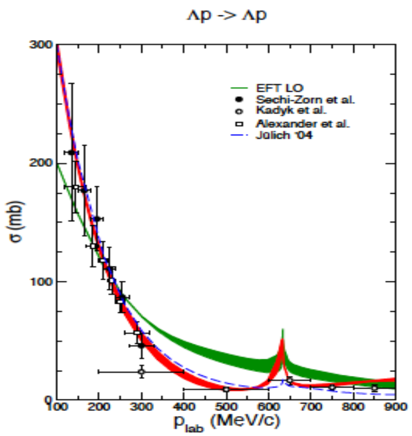
credit: A. Perez-Obiol

In Neutron Stars

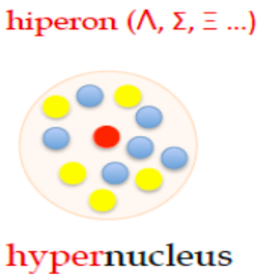


YN and YY interactions

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)

New data on femtoscopy!

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)$_{\text{flavor}}$ 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

- $V_{\text{low k}}$ approach

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

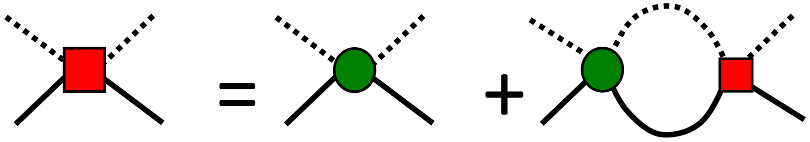
Schaefer, Wagner, Wambach, Kuo and Brown ‘06

- Lattice calculations (HALQCD/NPLQCD)

To solve YN and YY interactions on the lattice

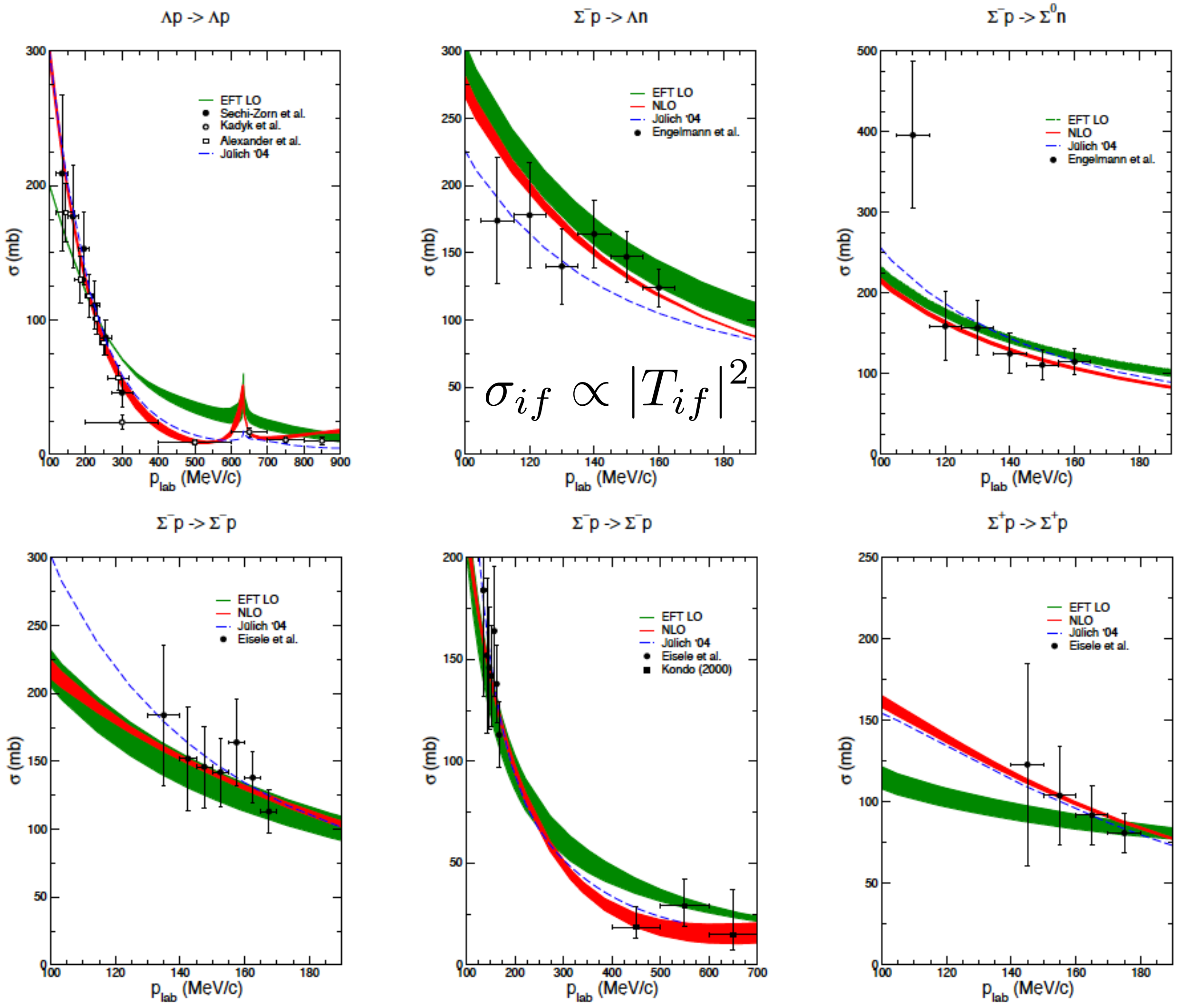
HALQCD: Ishii, Aoki, Hatsuda ‘07; Aoki, Hatsuda and Ishii ‘10; Aoki et al ‘12
NPLQCD: Beane, Orginos and Savage ‘11; Beane et al ’12

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

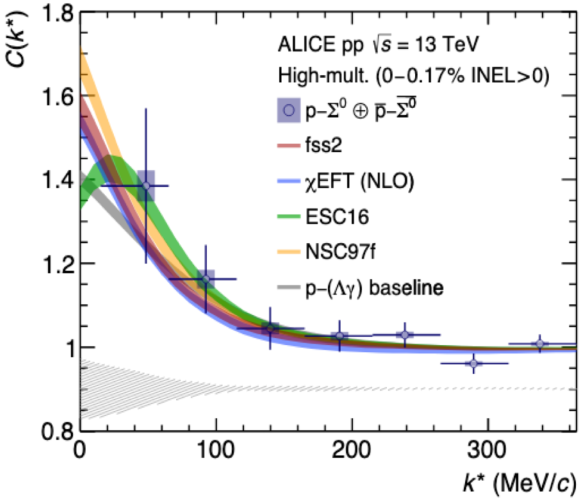


$$\sigma_{if} \propto |T_{if}|^2$$

New results from femtoscopy for **Σ^0p**

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

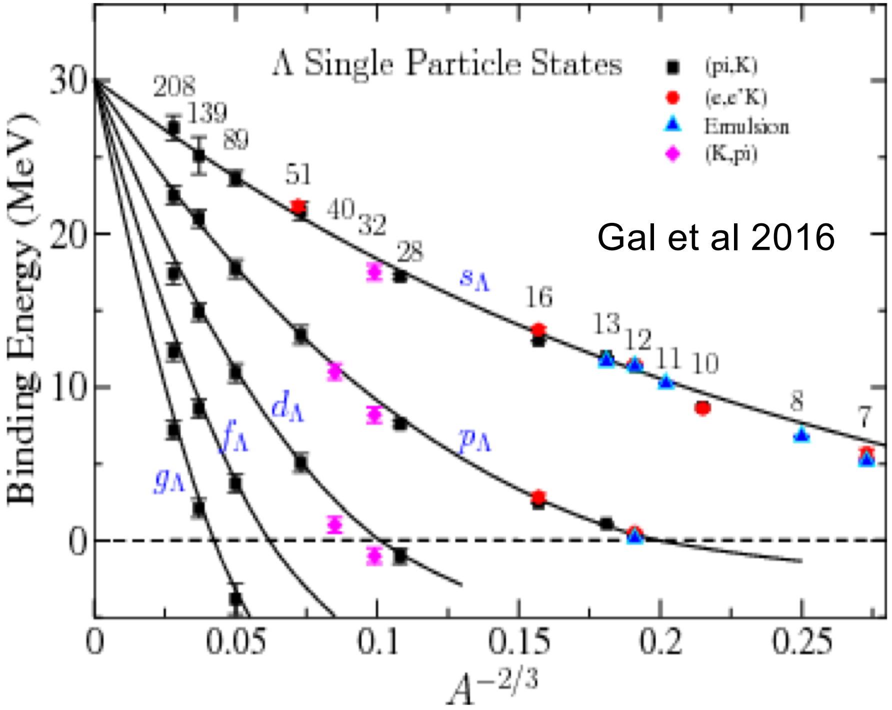
$$k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$$



S. Acharya et al. 2019

Hypernuclei

Binding energy of Λ hypernuclei



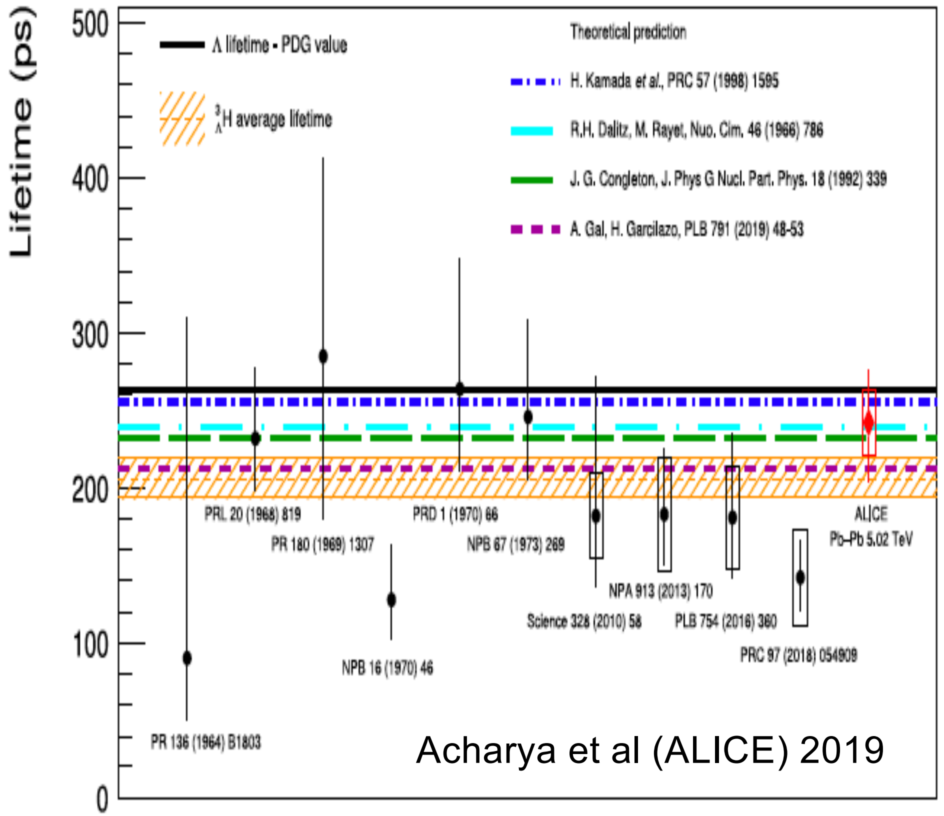
Gal et al 2016

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



Acharya et al (ALICE) 2019

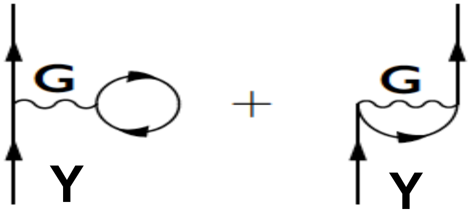
Expected $\tau({}^3{}_\Lambda H) = \tau(\Lambda)$

$\Leftrightarrow$ 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



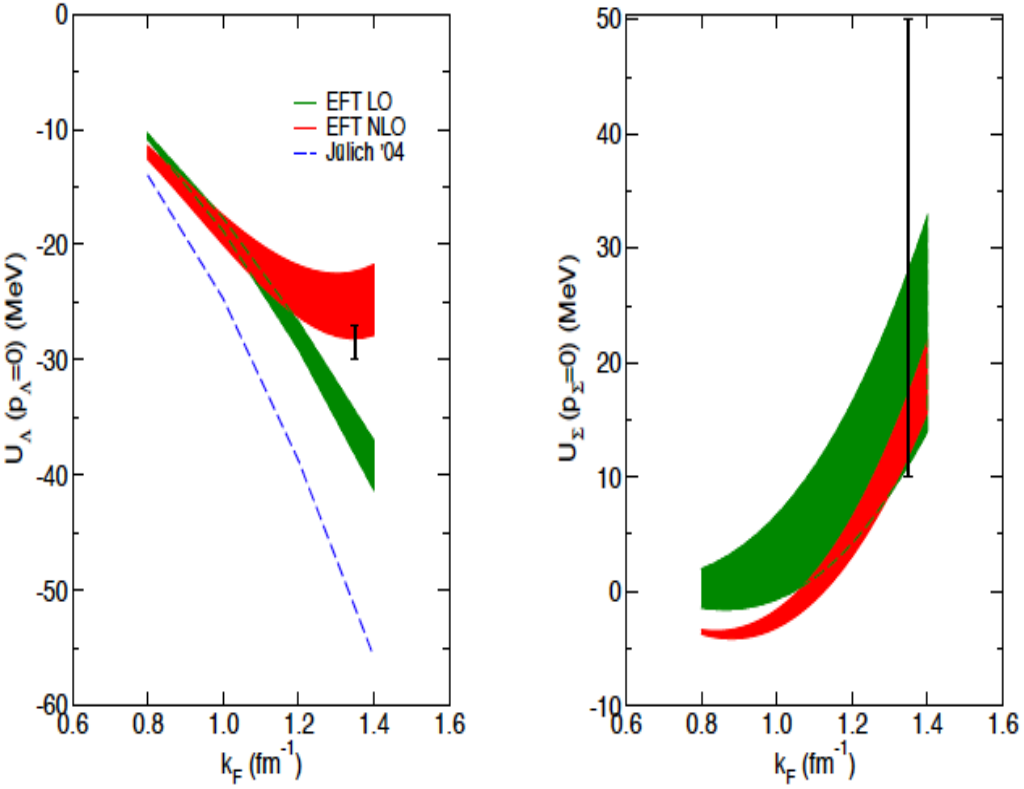
$$G = V + V\frac{Q_{\text{pauli}}}{E_0 - H_0}G$$

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

	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!



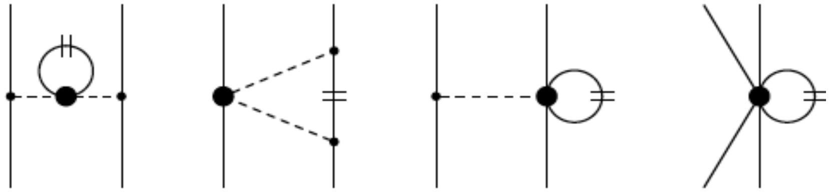
Haidenbauer and Meißner , NPA 936 (2015) 29

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

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

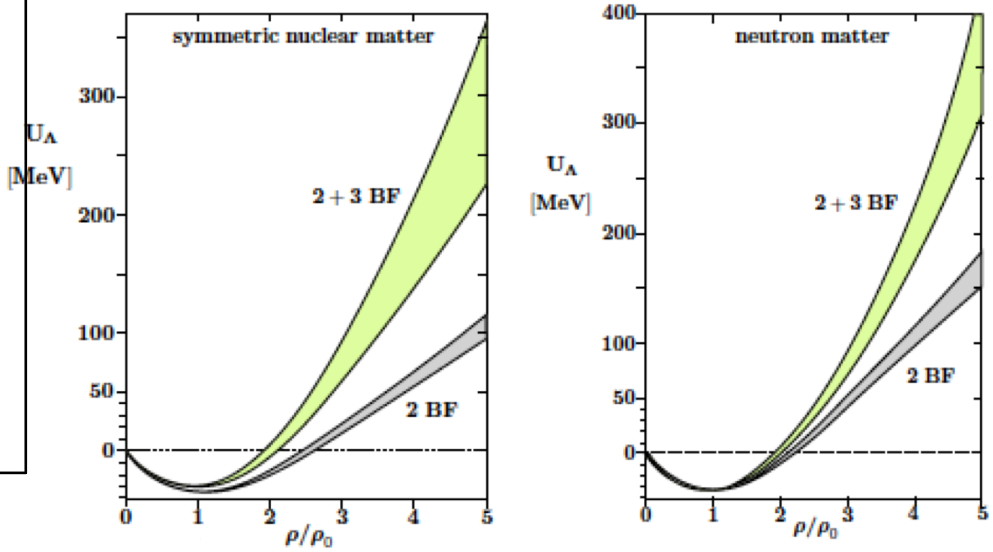
To use 3BF in many-body calculations, such as BHF, one has to construct a density-dependent two-body interaction

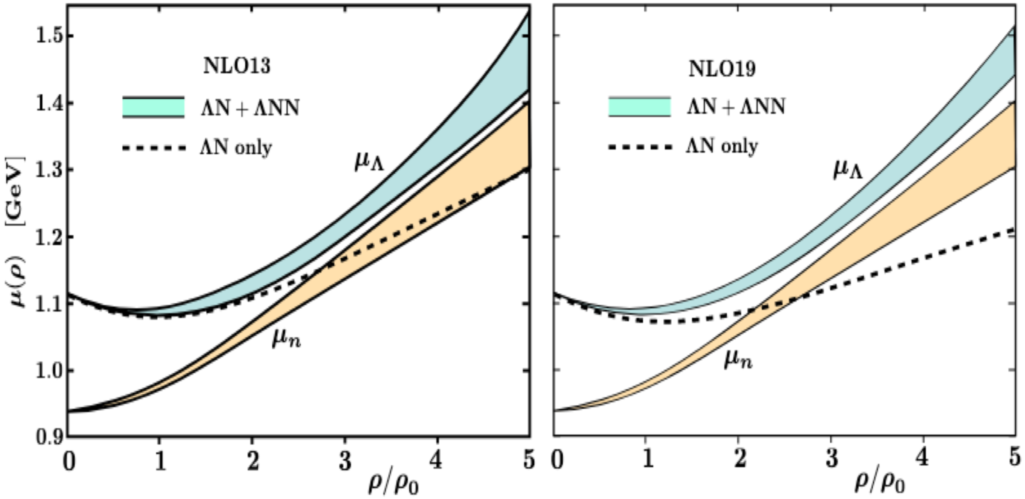


closing two baryon lines summing over the Fermi sea

credit: Haidenbauer

Λ in dense matter





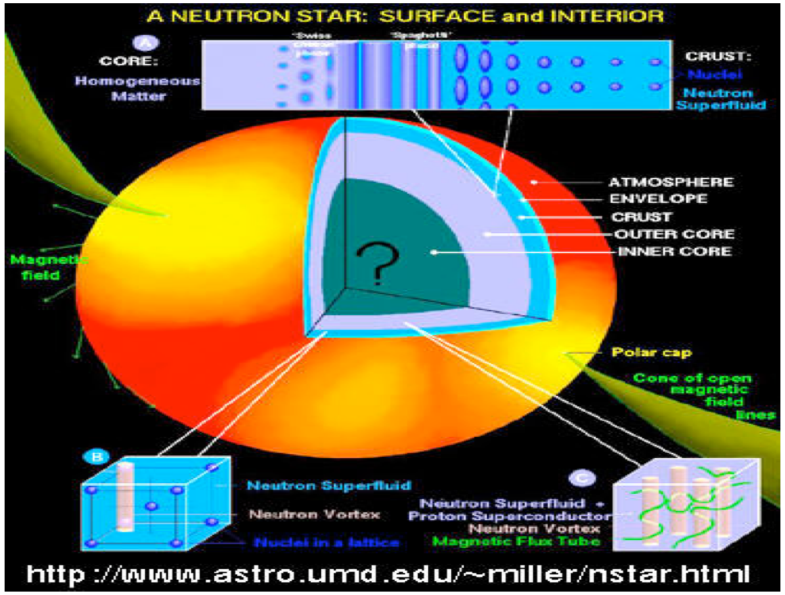
$\mu_\Lambda(\rho) \leq \mu_n(\rho) \Rightarrow$ energetically favorable to replace n by Λ

D. Gerstung et al. EPJA 56 (2020) 175

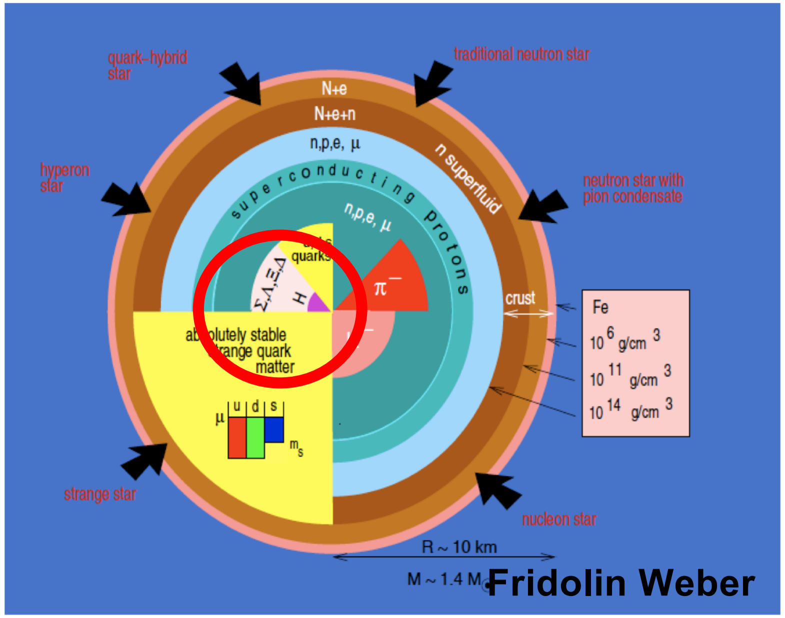
Λ hyperons will not appear in neutron stars (including 3BF)

Solution of the Hyperon Puzzle?

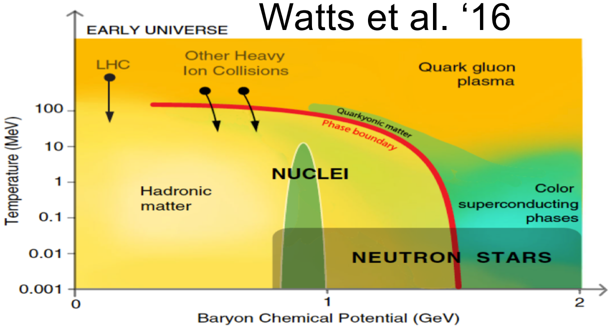
Hyperons and Neutron Stars



http ://www.astro.umd.edu/~miller/nstar.html



Fridolin Weber



Watts et al. ‘16

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

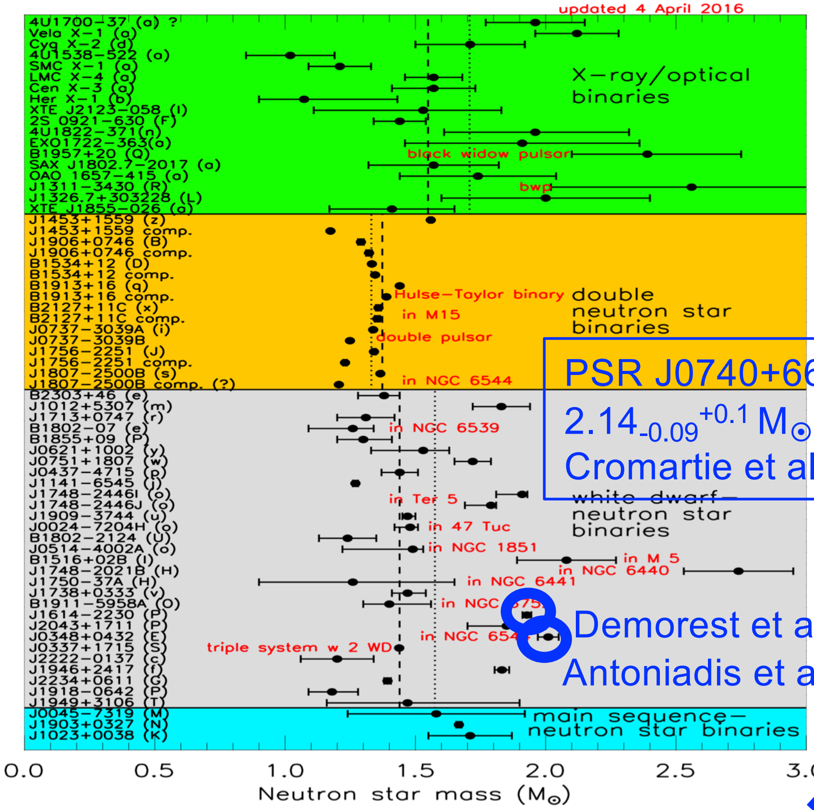
- magnetic field : $B \sim 10^{8..16}$ G

- temperature: $T \sim 10^{6\dots11}$ 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

8

Demorest et al '10

Antoniadis et al '13

Radius

NICER

PSR J0030+0451

$R_{eq} = 13.02_{-1.06}^{+1.24}$ km

$M = 1.44_{-0.14}^{+0.15}$ $M_\odot$

Miller et al. '19

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

$M = 1.34_{-0.16}^{+0.15}$ $M_\odot$

Riley et al. '19

NICER

PSR J0740+6620

$R_{eq} = 13.71_{-1.5}^{+2.6}$ km

$M = 2.08_{-0.07}^{+0.07}$ $M_\odot$

Miller et al. '21

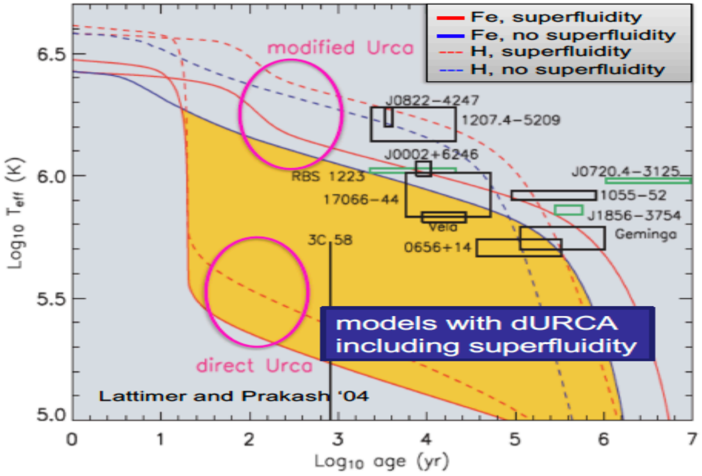
$R_{eq} = 12.39_{-0.98}^{+1.30}$ km

$M = 2.072_{-0.066}^{+0.067}$ $M_\odot$

Riley et al. '21

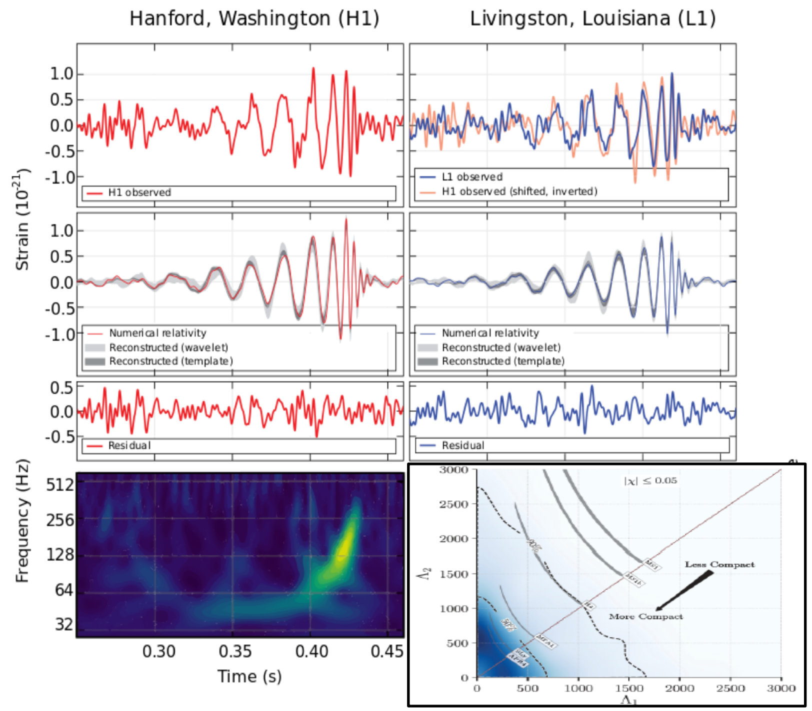
Observations

Cooling



GW170817

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



..also GW190814, GW250419?

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

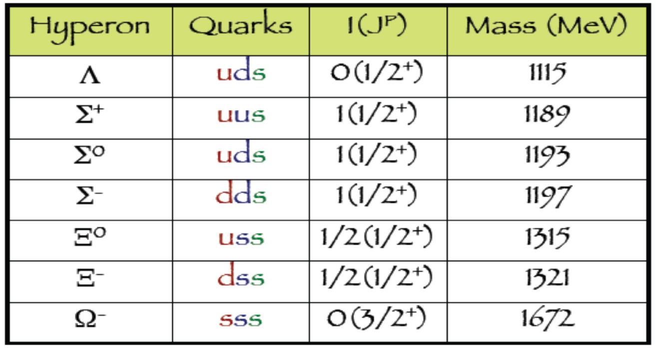
- *Non-relativistic EDF: Skyrme..*
- *Relativistic Mean-Field (RMF) and Relativistic Hartree-Fock (RHF)*
- *Liquid Drop Model: BPS, BBP,..*
- *Thomas-Fermi model: Shen*
- *Statistical Model: HWN,RG,HS..*

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

What about Hyperons?

First proposed in 1960 by Ambartsumyan & Saakyan

credit: Vidana



Hyperon	Quarks	$I(J^P)$	Mass (MeV)
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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

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

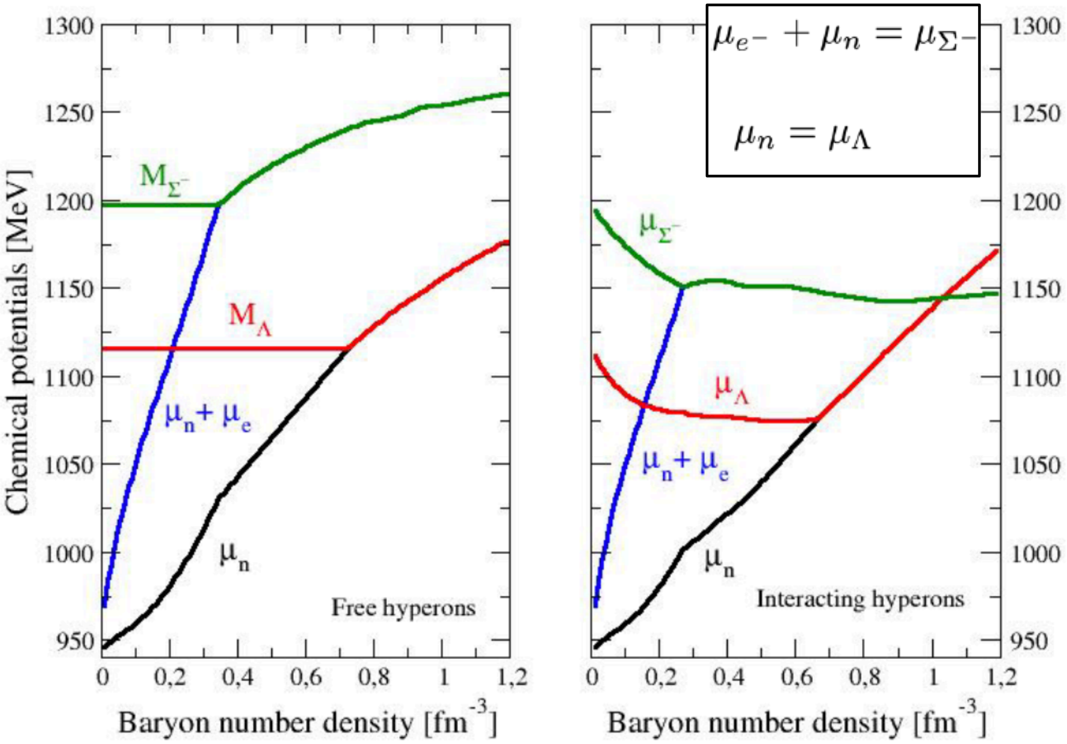
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

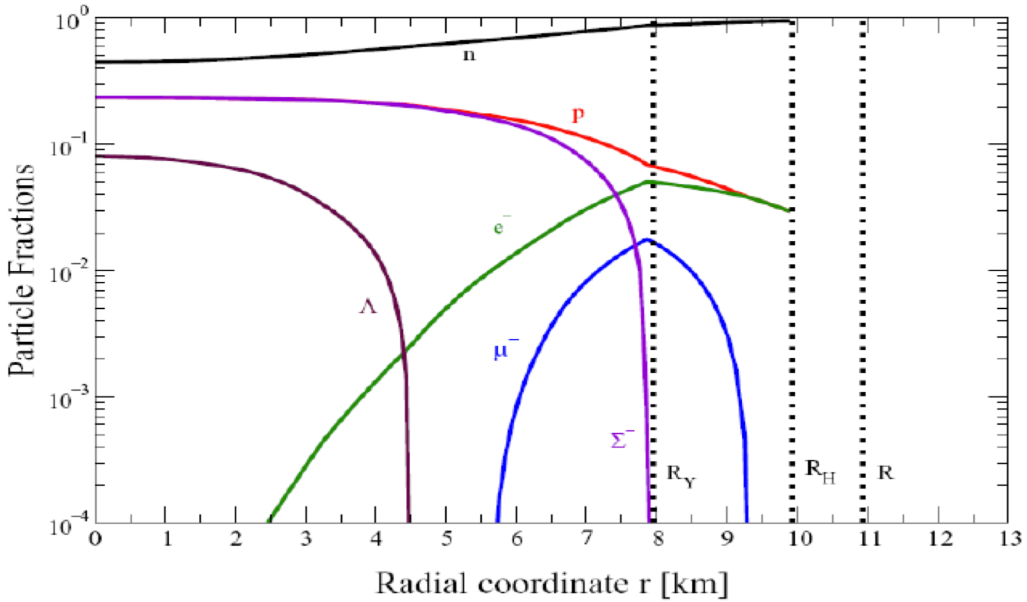
$$n + n \rightarrow p + \Sigma^-$$

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

$$\mu_i = b_i \mu_n - q_i \mu_e$$

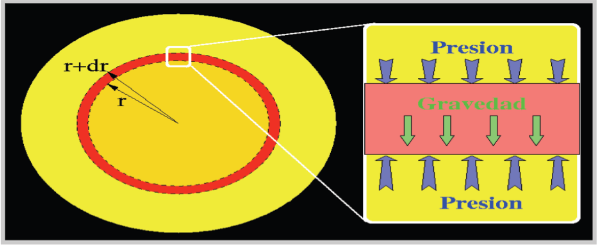
$$\sum_i x_i q_i = 0$$



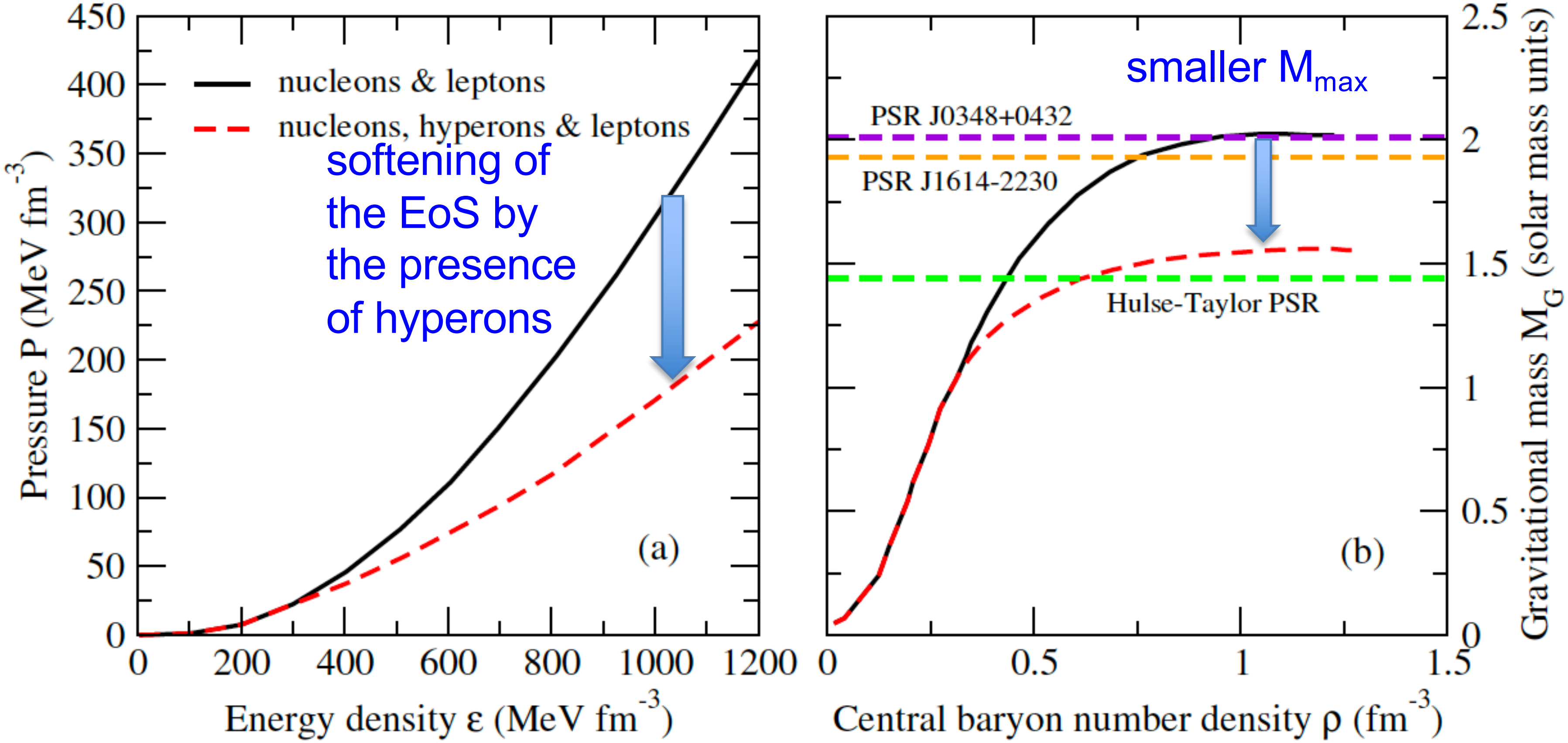


credit: Vidana

Inclusion of hyperons….



Credit:
Dani P. Page



softening of the EoS by the presence of hyperons

smaller M_{max}

….. 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

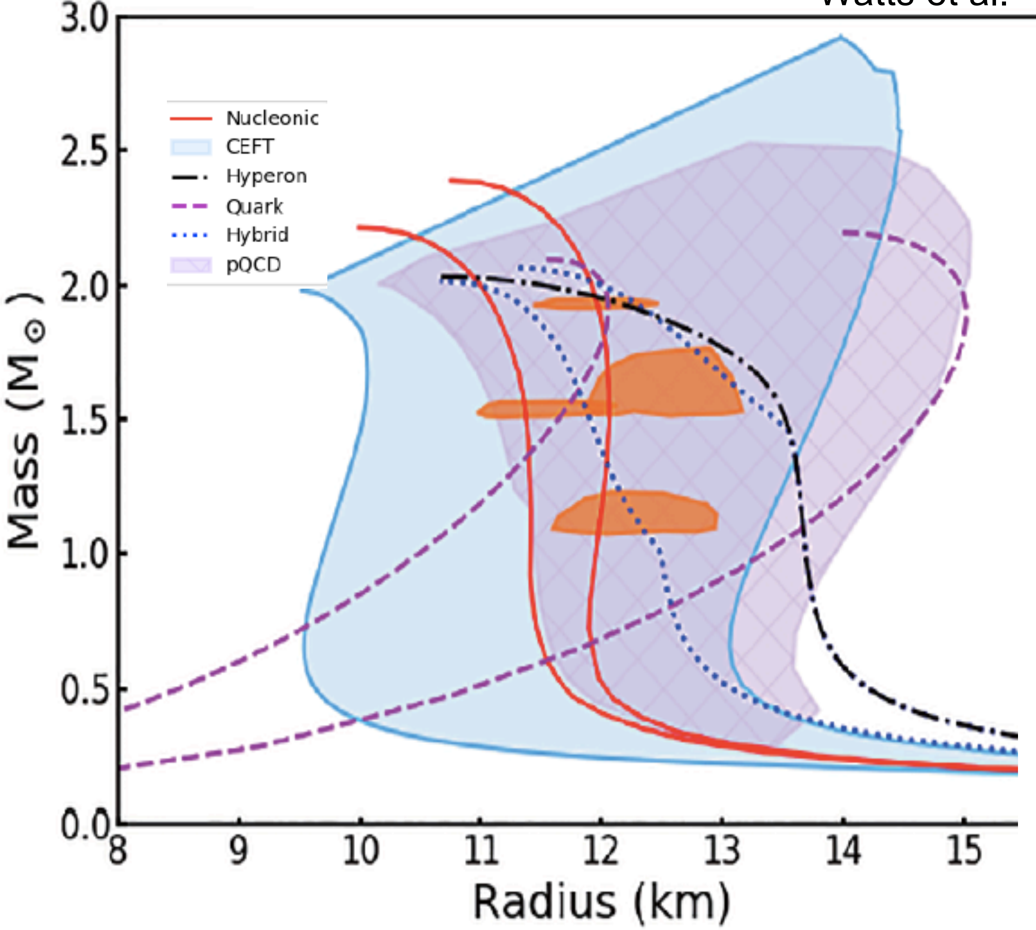
- YN data from femtoscopy

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$_\odot$**

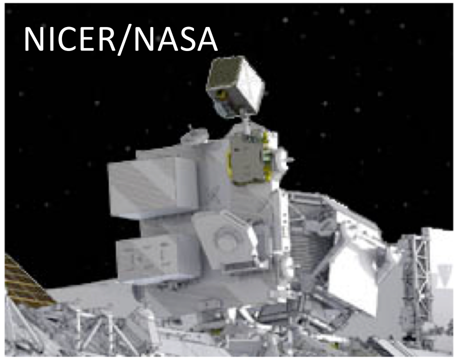
Solution?

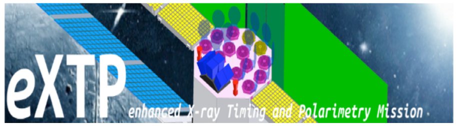
- ➢ stiffer YN and YY interactions
- ➢ hyperonic 3-body forces
- ➢ push of Y onset by Δ-isobars or meson condensates
- ➢ quark matter below Y onset
- ➢ dark matter, modified gravity theories…

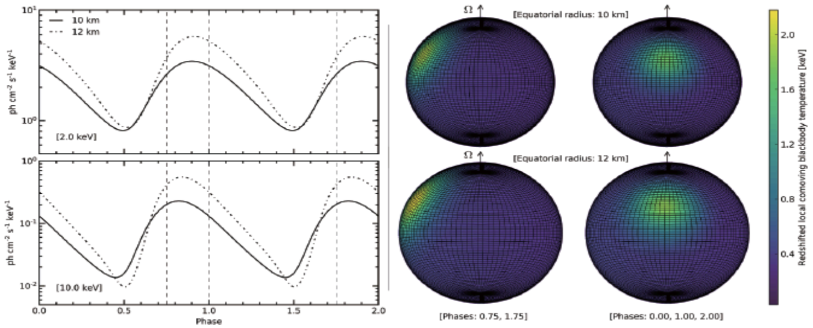
Future: space missions to study the interior of NS



Watts et al. ‘19



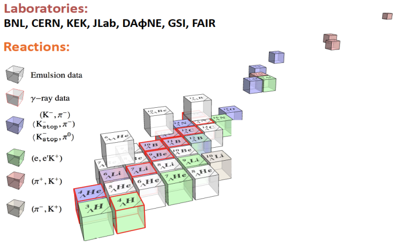


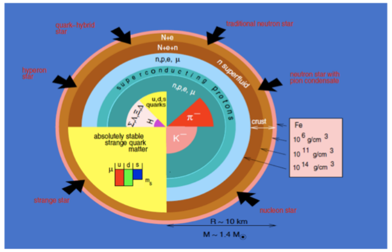


Constraints from pulse profile modelling of rotation-powered pulsars with eXTP

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 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

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS
DFG Deutsche Forschungsgemeinschaft
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN
THOR
STRONG 2020