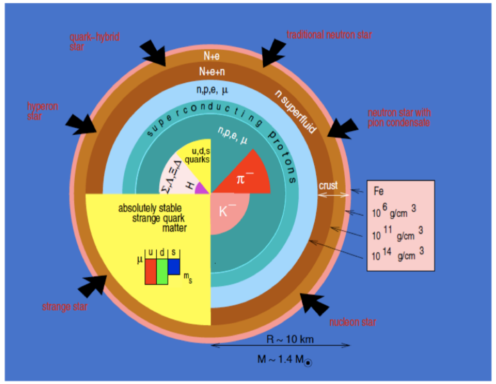
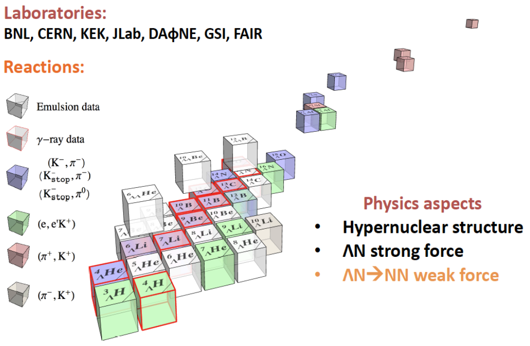




Laboratories:
BNL, CERN, KEK, JLab, DAΦNE, GSI, FAIR

Reactions:

Physics aspects

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

Hyperon interactions: the state-of-the-art and applications

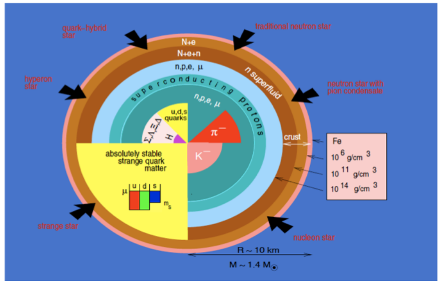
Institute of Space Sciences
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
IEEC

Laura Tolós

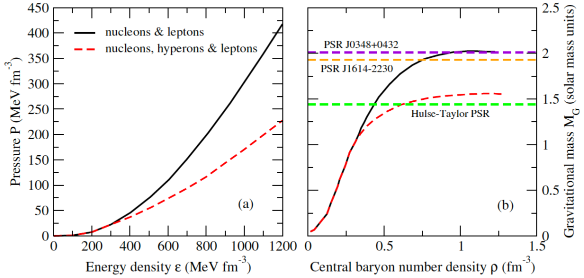
FIAS Frankfurt Institute for Advanced Studies

Physics opportunities with proton beams at SIS100

6-9 February 2024
Wuppertal University
Europe/Berlin timezone



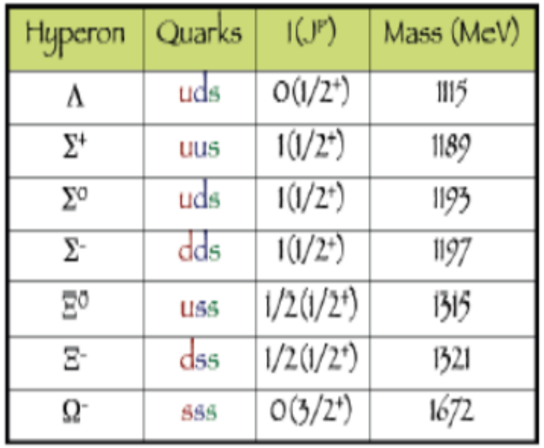
Outline



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

Hyperons and where to find them

A hyperon is a baryon containing one or more strange quarks



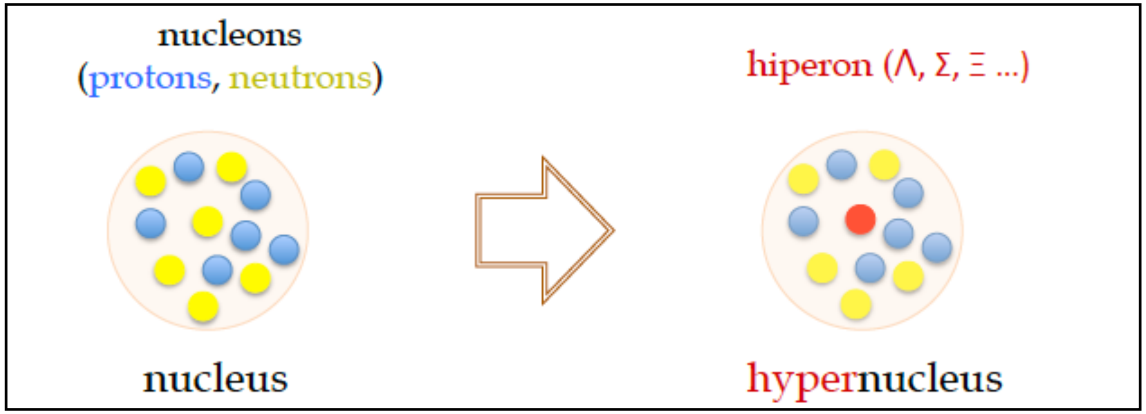
Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

credit: I. Vidana

The study of hypernucleus allows for

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

On Earth: Hypernuclei

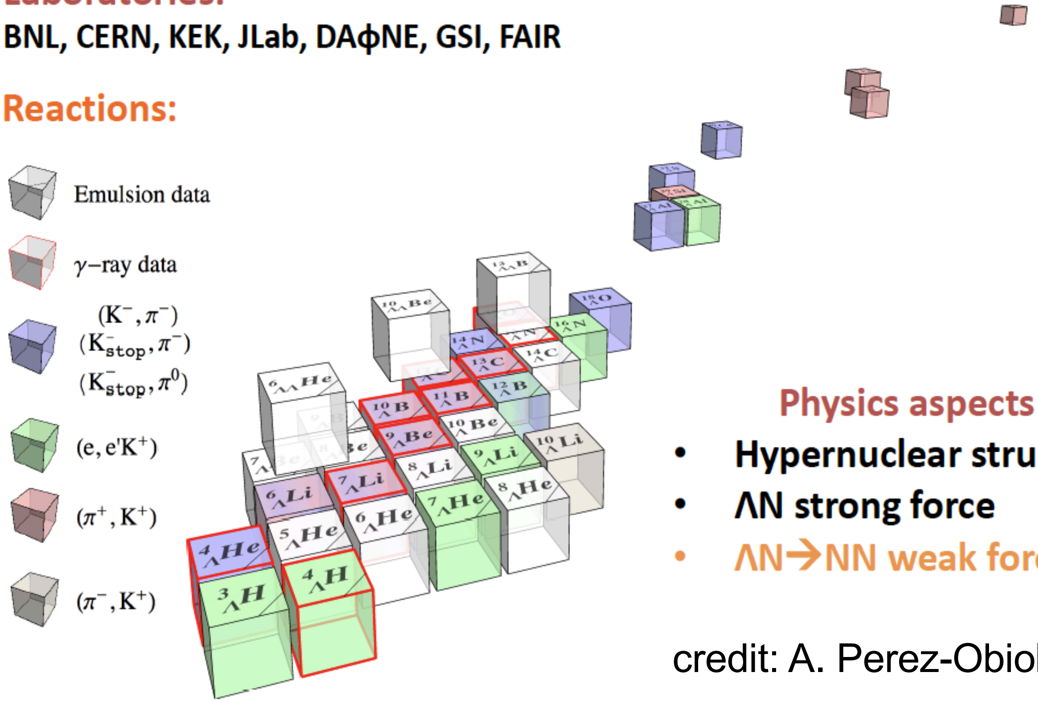


credit: A. Parreno

Laboratories:

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

Reactions:

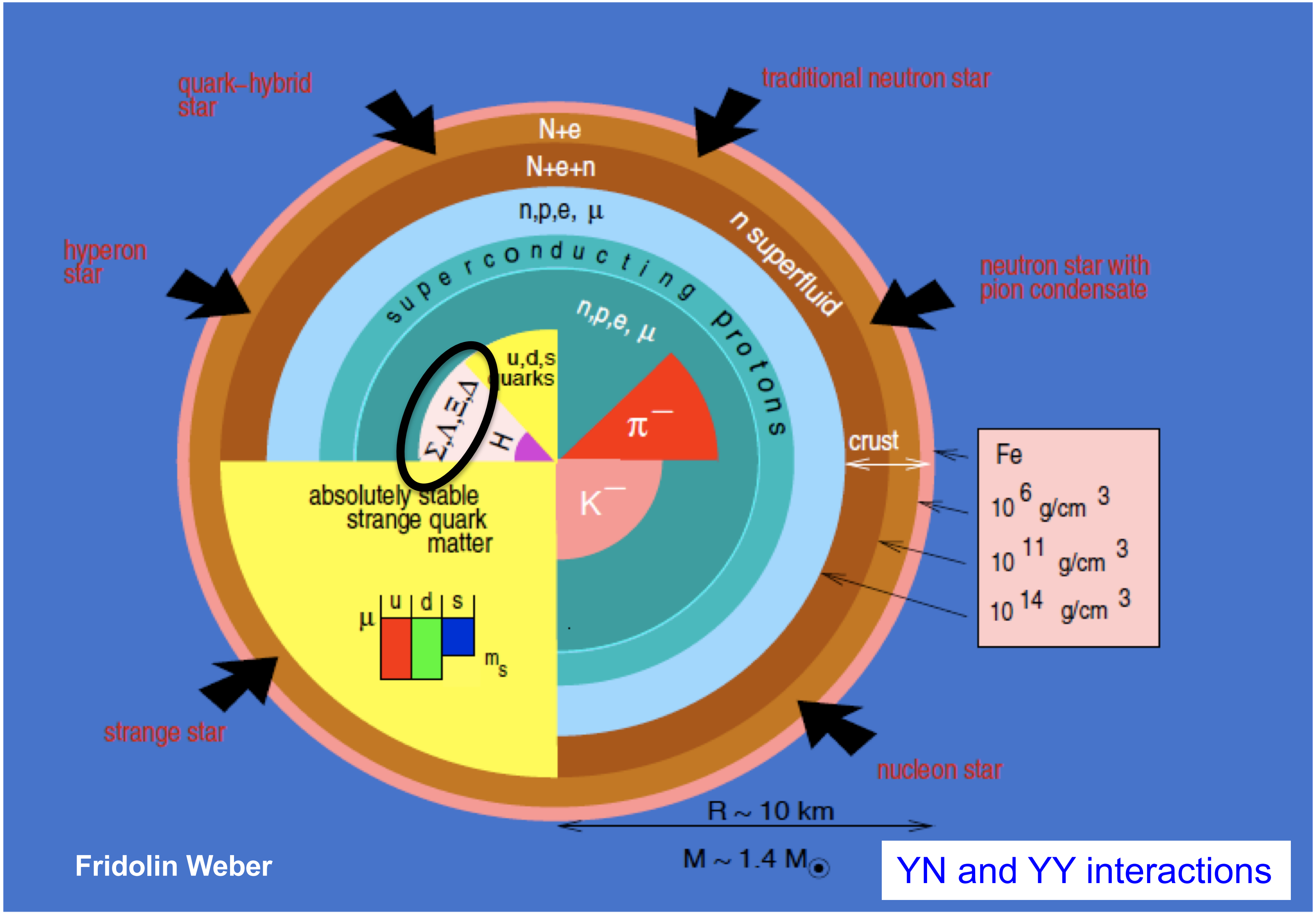


Physics aspects

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

credit: A. Perez-Obiol

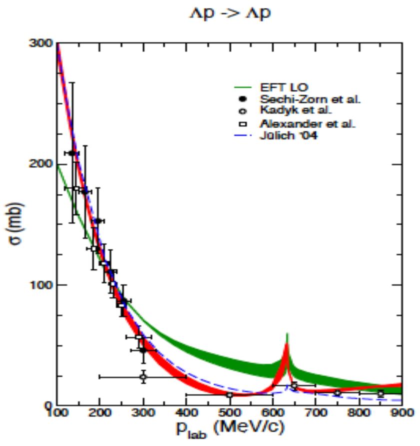
In Neutron Stars



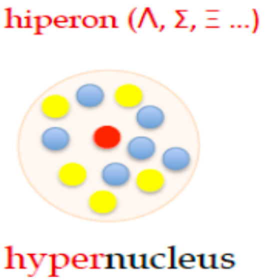
Fridolin Weber

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 (*ΛΛ* weak attraction)
- few Ξ-hypernuclei (ΞN attractive)
- evidence of 1 Σ-hypernuclei ? (ΣN repulsive)

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

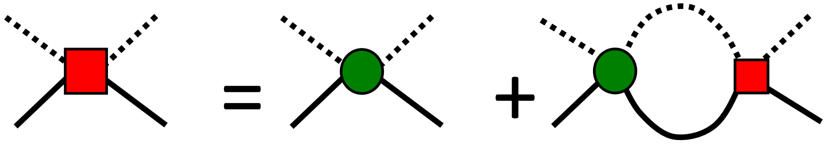
Schaefer, Wagner, Wambach, Kuo and Brown '06

- Lattice calculations (HALQCD/NPLQCD)

To solve YN and YY interactions on the lattice

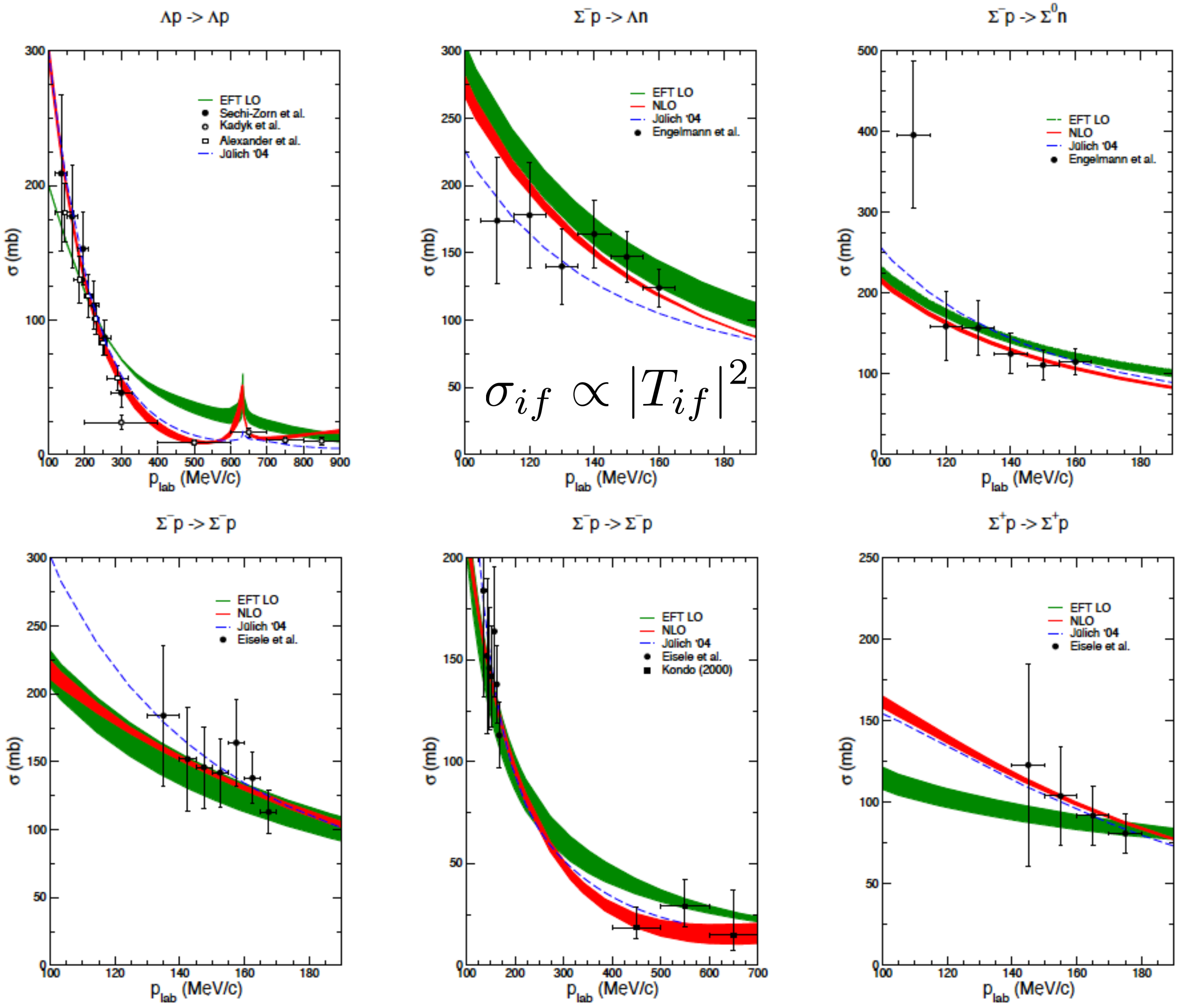
HALQCD: Ishii, Aoki, Hatsuda '07; Aoki, Hatsuda and Ishii '10; Aoki et al '12
NPLQCD: Beane, Orginos and Savage '11; Beane et al '12

ΛN and ΣN scattering



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

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

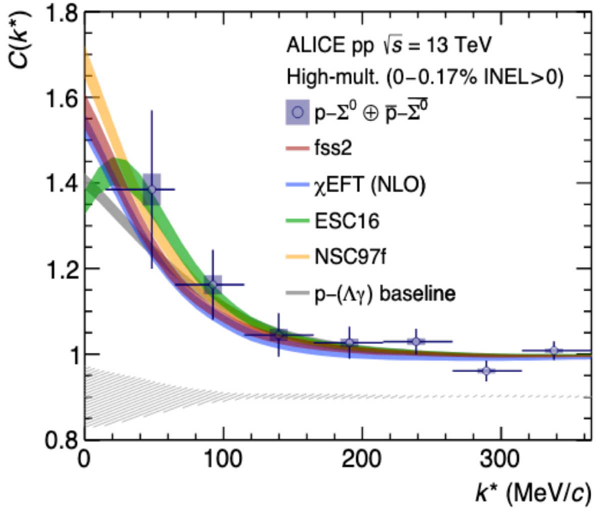


$$\sigma_{if} \propto |T_{if}|^2$$

New results from femtoscopy for $\mathbf{\Sigma^0 p}$

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

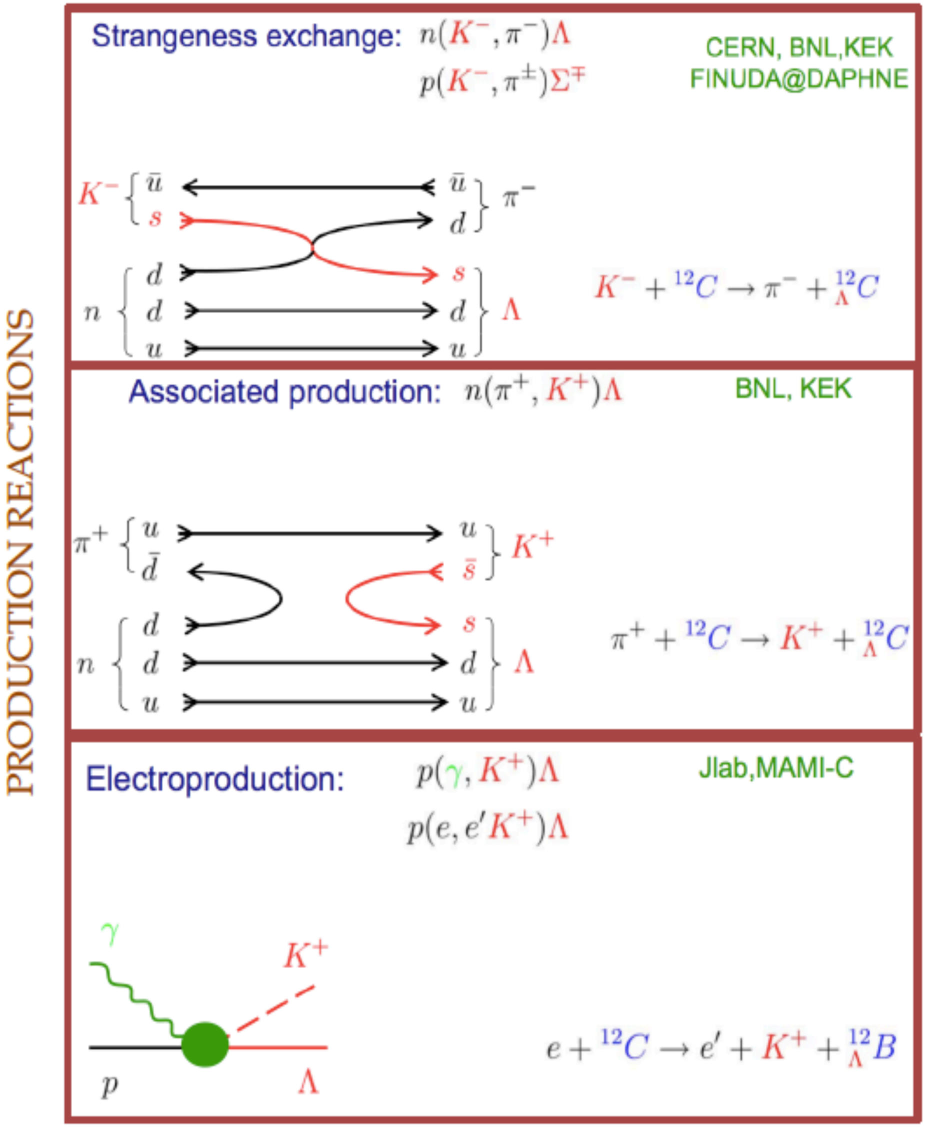
$$k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$$



S. Acharya et al. 2019

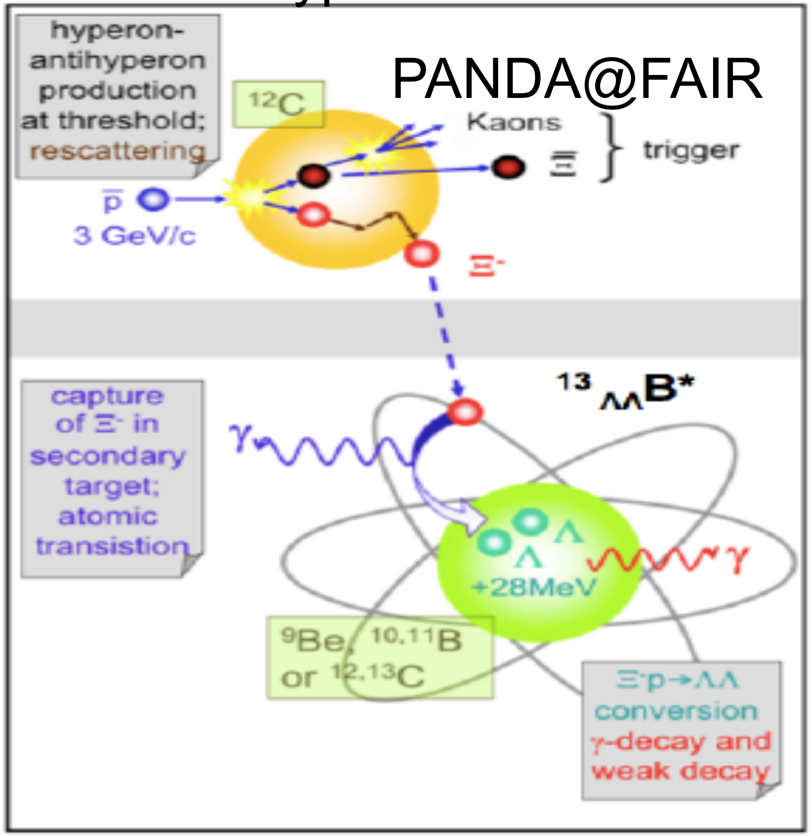
Hypernuclei

Λ hypernuclei



credit: A. Parreno

Double Λ hypernuclei



credit: A. Sanchez-Lorente

Also Ξ hypernuclei @ BNL, KEK

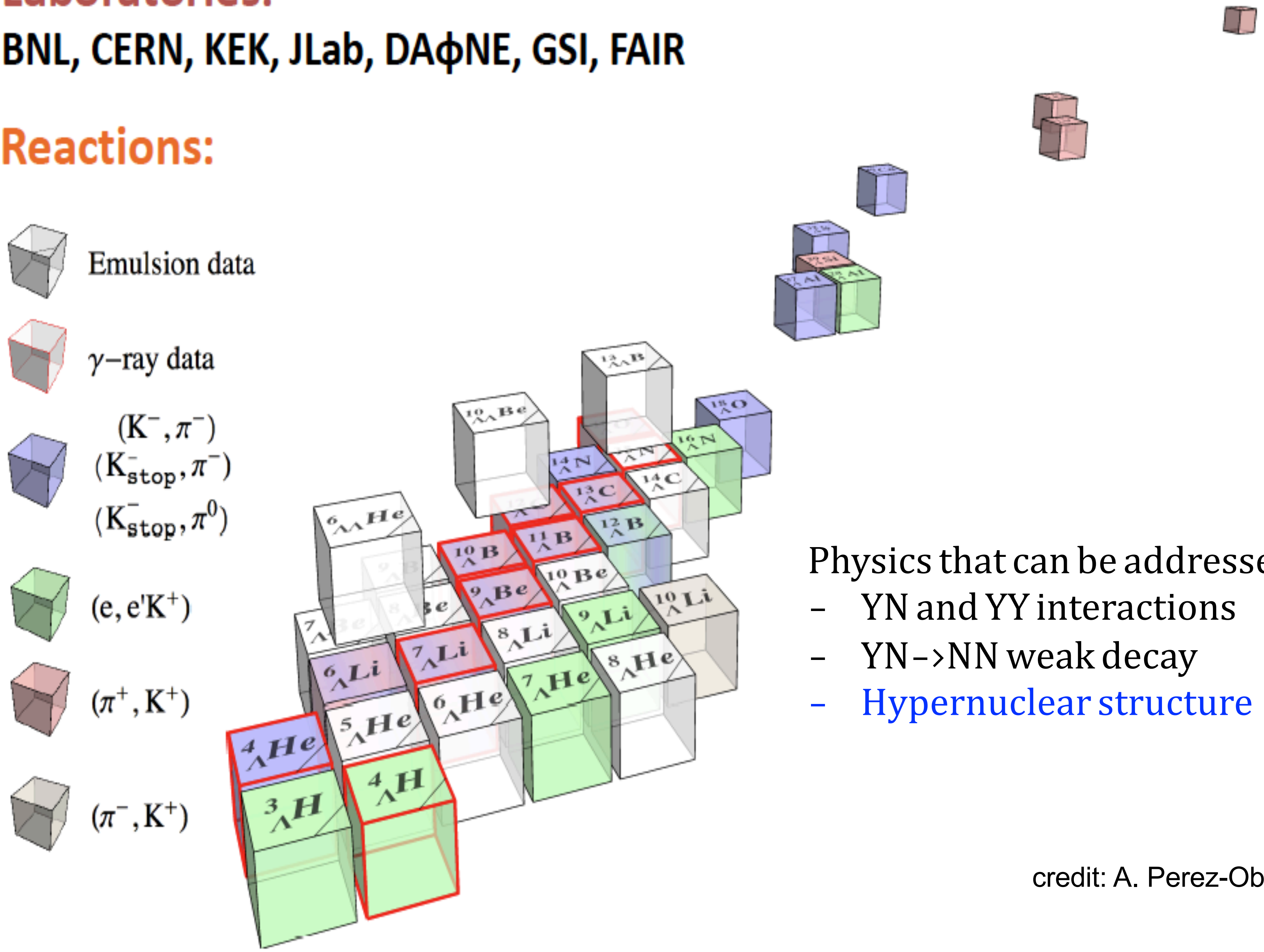
$$^{12}\mathrm{C}(K^-,K^+)^{12}_{\Xi^-}\mathrm{Be}$$

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

Laboratories:

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

Reactions:

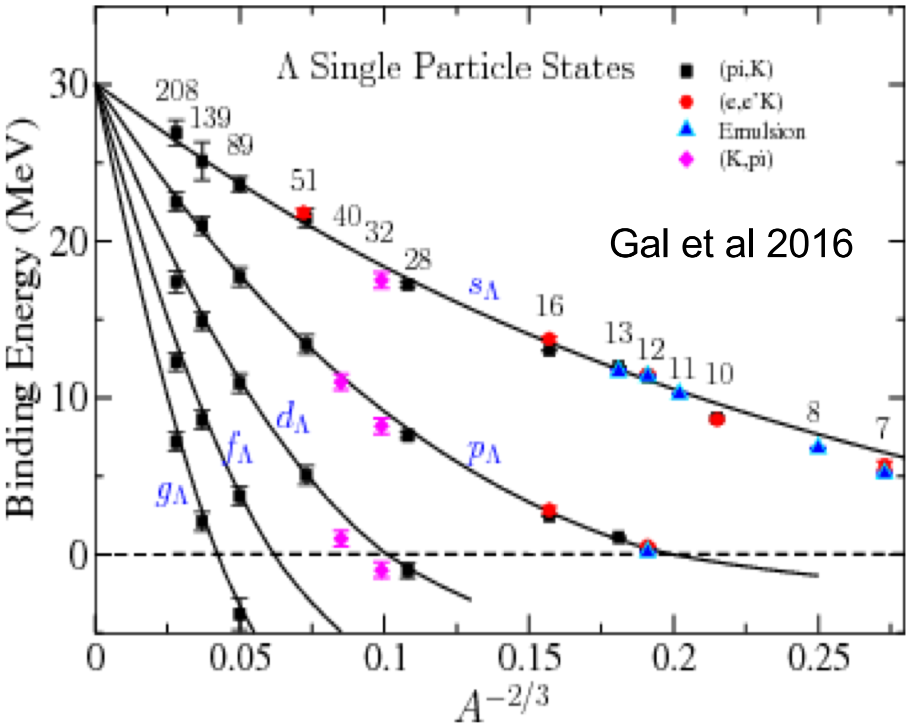


Physics that can be addressed：

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

credit: A. Perez-Obiol

Binding energy of Λ hypernuclei

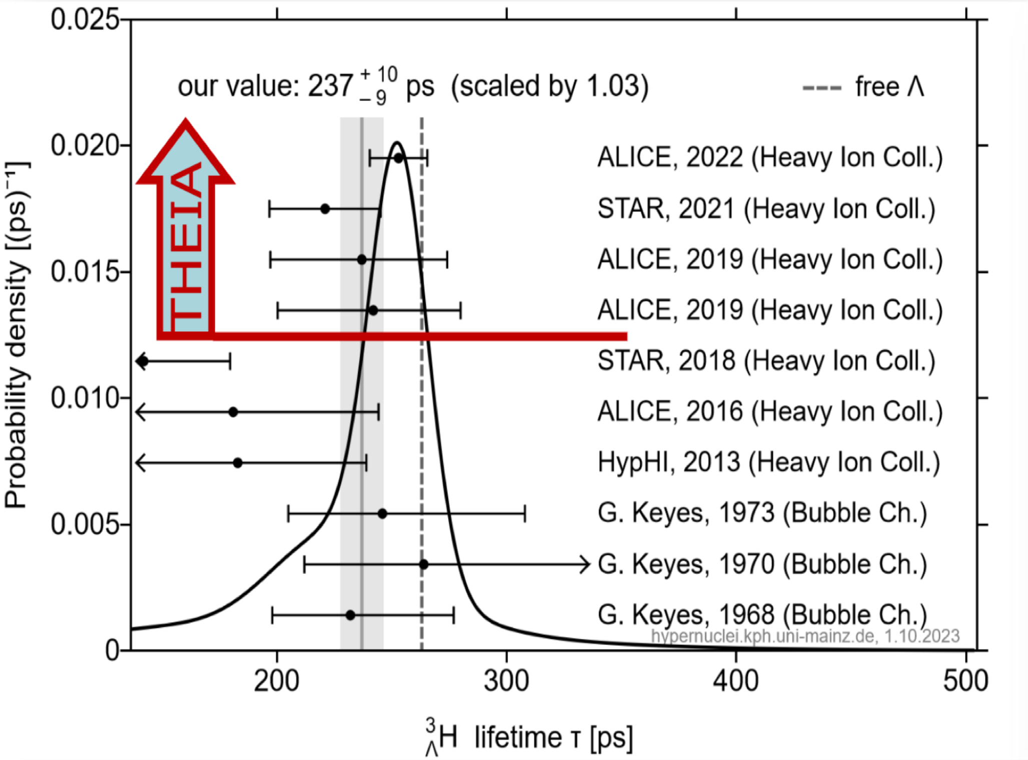


Binding energy of different hypernuclei as function of the mass number

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

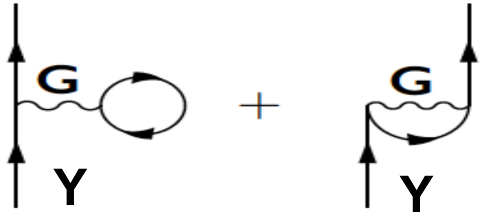
$\Leftrightarrow$ observed: $\tau(^{3}_{\Lambda}H) < \tau(\Lambda)$

Conflicting measurements by STAR(2018) and ALICE(2019) of the hypertriton lifetime triggered the revived experimental and theoretical interest.

Recent data solved the puzzle!

Hyperons in matter

Λ and Σ in dense matter



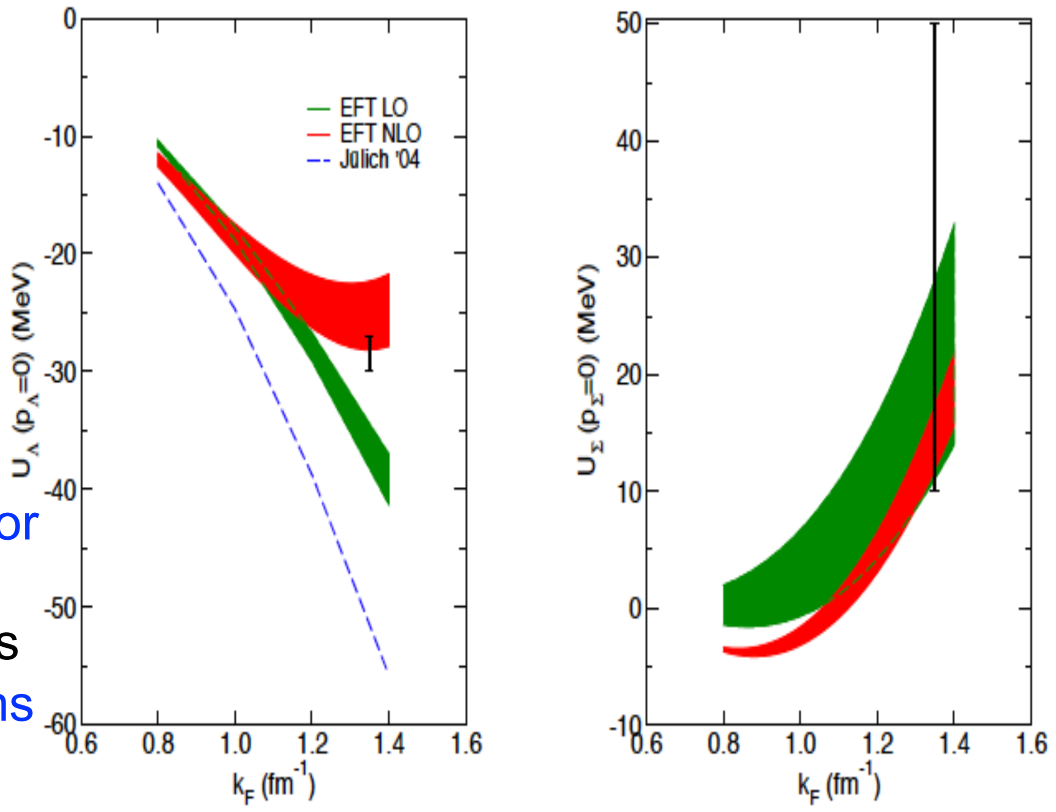
$$G = V + V\frac{Q_{\text{pauli}}}{E_0 - H_0}G$$

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

	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): discussion about repulsion or attraction, where $^3S_1$-$^3D_1$ component is decisive. A repulsive $^3S_1$-$^3D_1$ interaction is chosen in accordance to data on Σ^- atoms and (π^-,K^+) inclusive spectra for Σ^- formation in heavy nuclei as well as lattice* indications



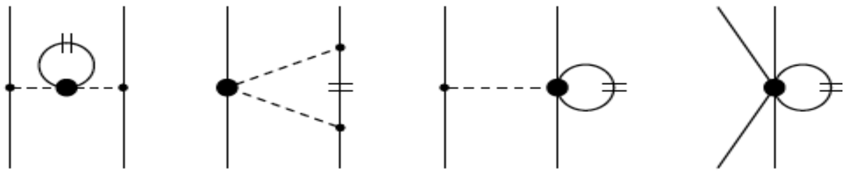
Haidenbauer and Meißner , NPA 936 (2015) 29

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

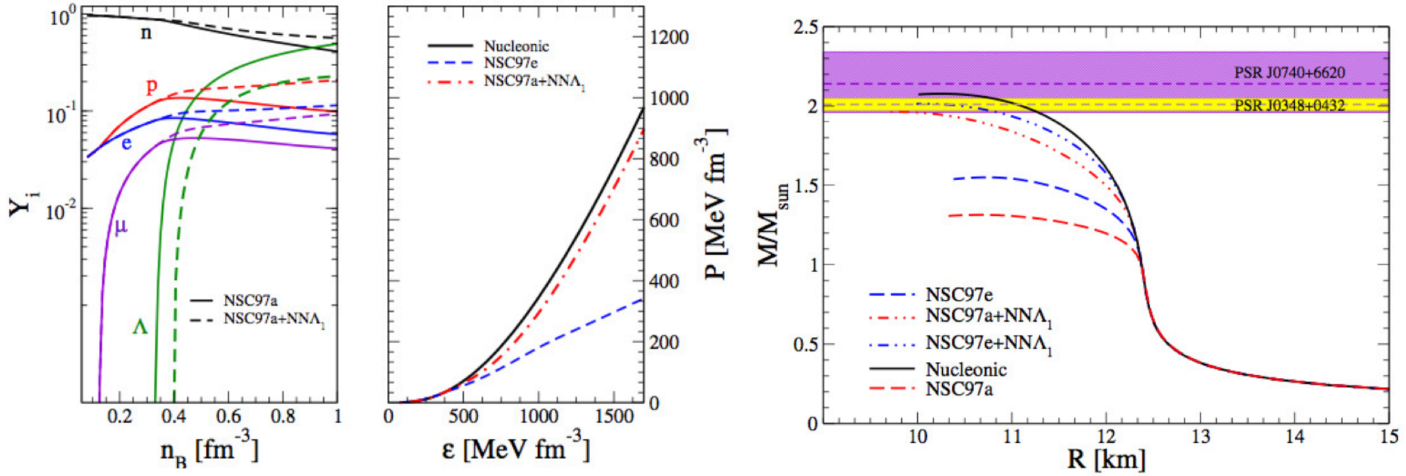
Λ in dense matter: including three-body forces

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

credit: Haidenbauer



Λ in dense matter in χEFT: Hyperon puzzle?

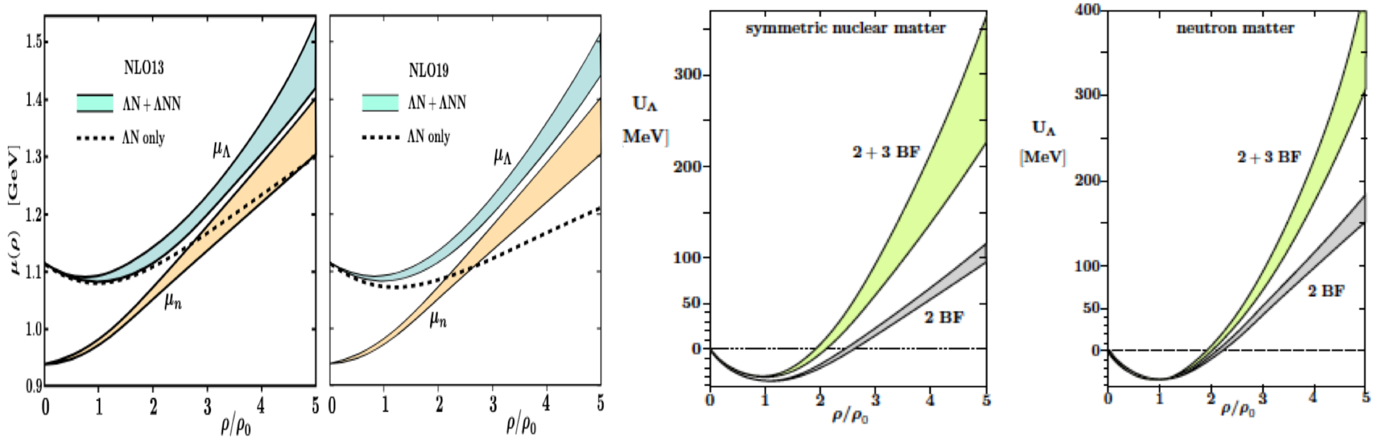


NS matter as mixture of n,p,e^-,μ^-,Λ in β-equilibrium

χEFT (NN, NNN,NNΛ) + meson-exchange (NY)

Λ concentration is small but still present in $2M_\odot$ NS

Logoteta, Vidana and Bombaci EPJA 55 (2019) 207



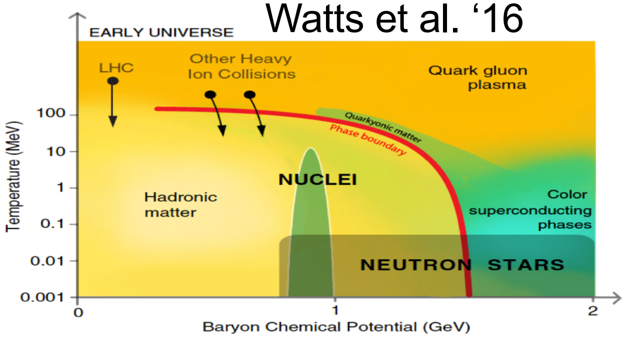
Only symmetric and neutron matter

χEFT NN, NNN,NY, NNY

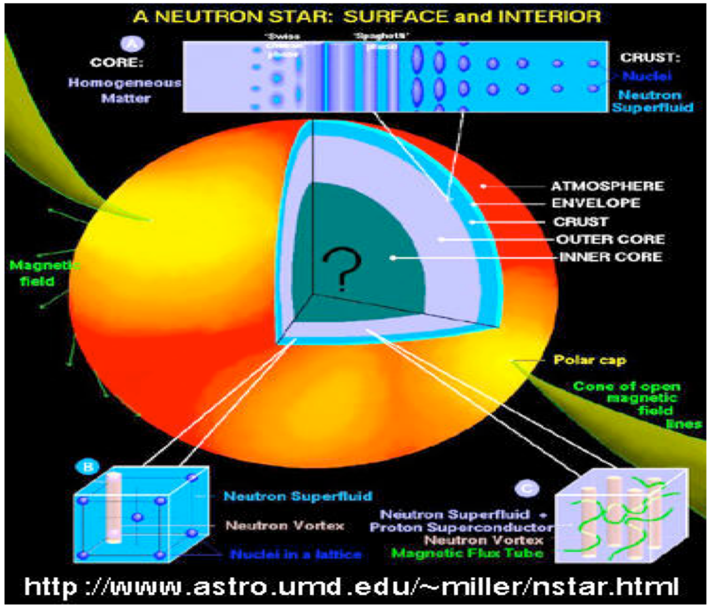
Λ in NS energetically unfavorable, but only neutrons and Λ are considered

Gerstung, Kaiser and Weise EPJA 56 (2020) 175

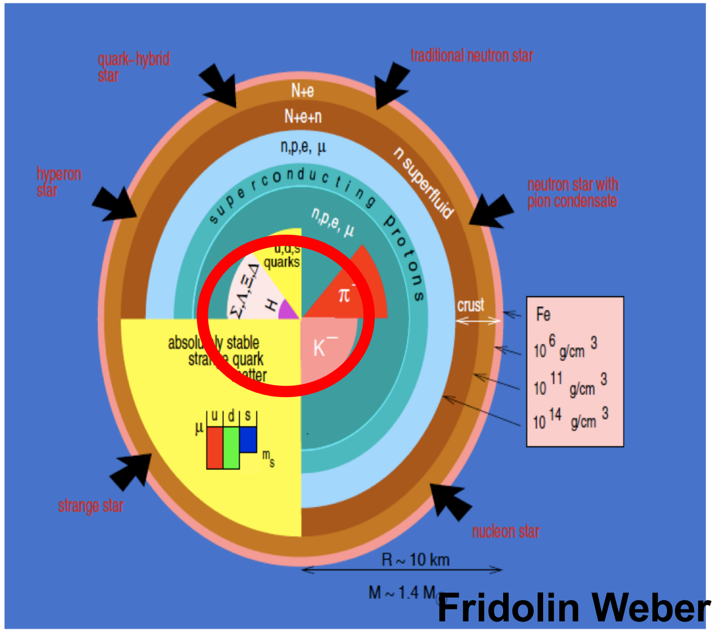
Hyperons and Neutron Stars



Watts et al. '16



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



Fridolin Weber

- 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

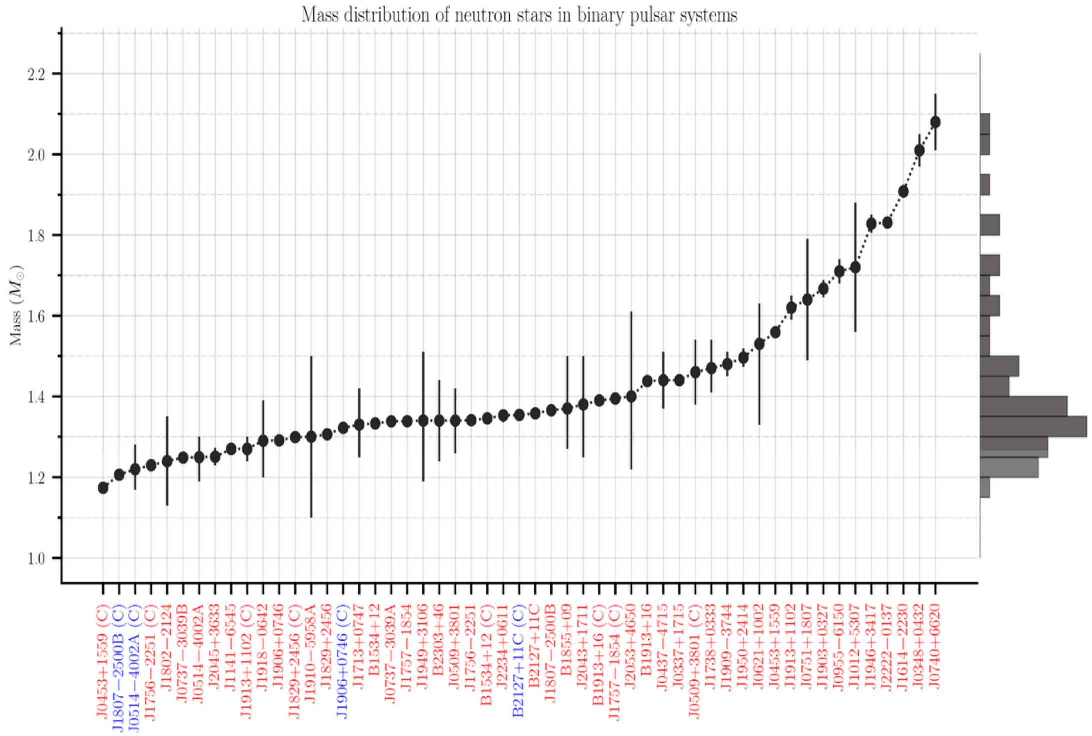
- temperature: $T \sim 10^{6\dots11}$ K

- observations: masses, radius, gravitational waves…

Observations

Masses

credit: P. Freire



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

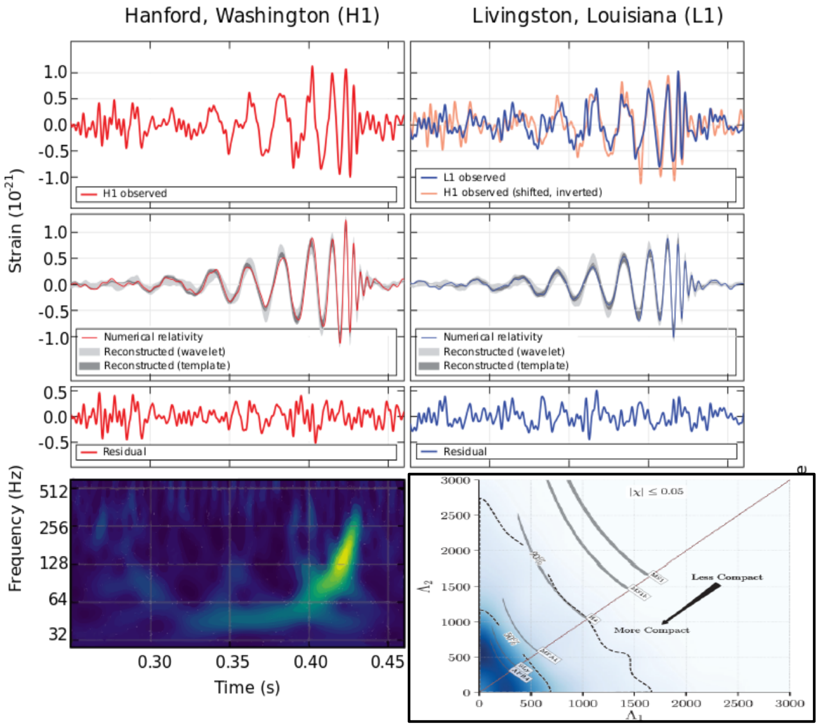
NICER
PSR J0740+6620

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

GW170817

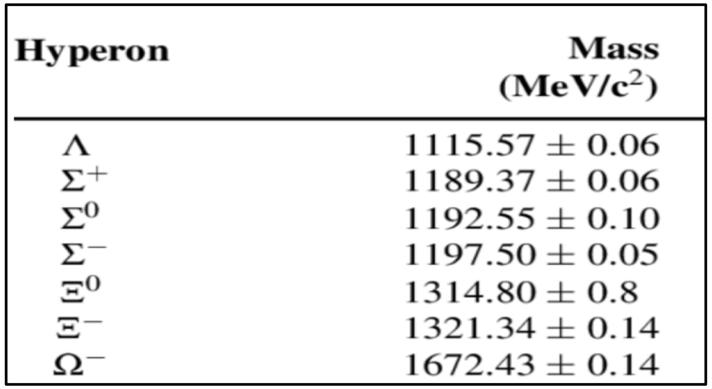
Abbot et al. (LIGO-VIRGO) '17 '18



..also GW190425, GW190814

What about Hyperons?

First proposed in 1960 by
Ambartsumyan & Saakyan



Hyperon	Mass (MeV/c^2)
Λ	1115.57 ± 0.06
Σ^+	1189.37 ± 0.06
Σ^0	1192.55 ± 0.10
Σ^-	1197.50 ± 0.05
Ξ^0	1314.80 ± 0.8
Ξ^-	1321.34 ± 0.14
Ω^-	1672.43 ± 0.14

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

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

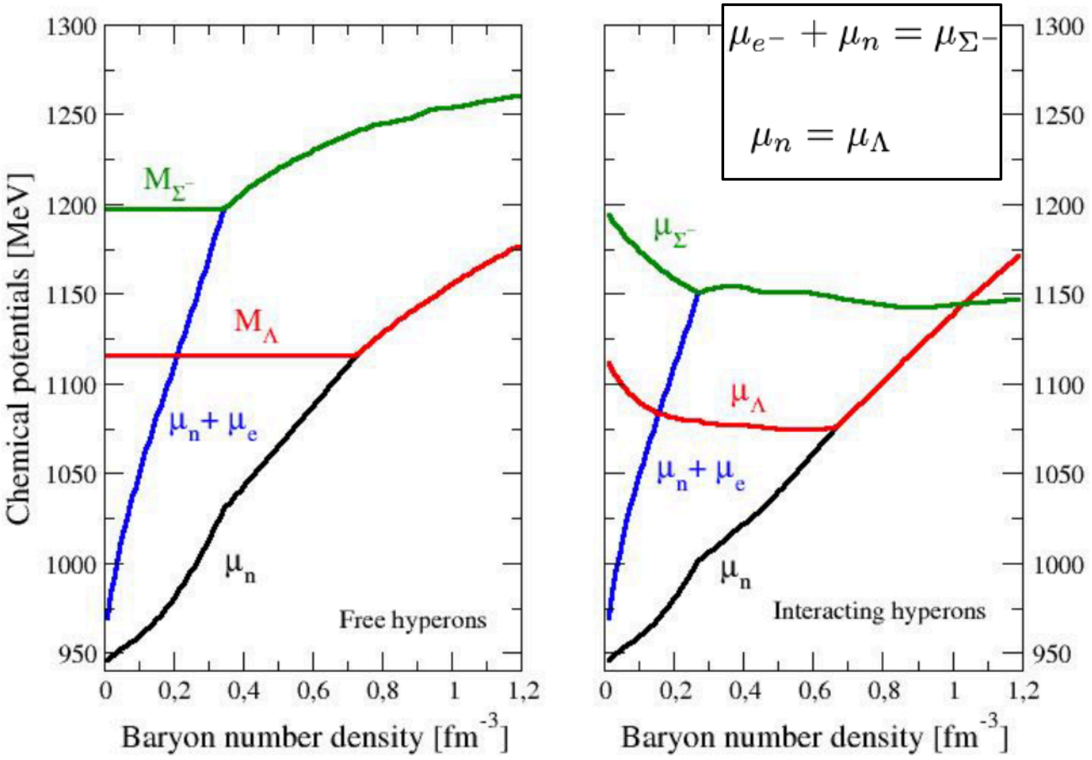
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

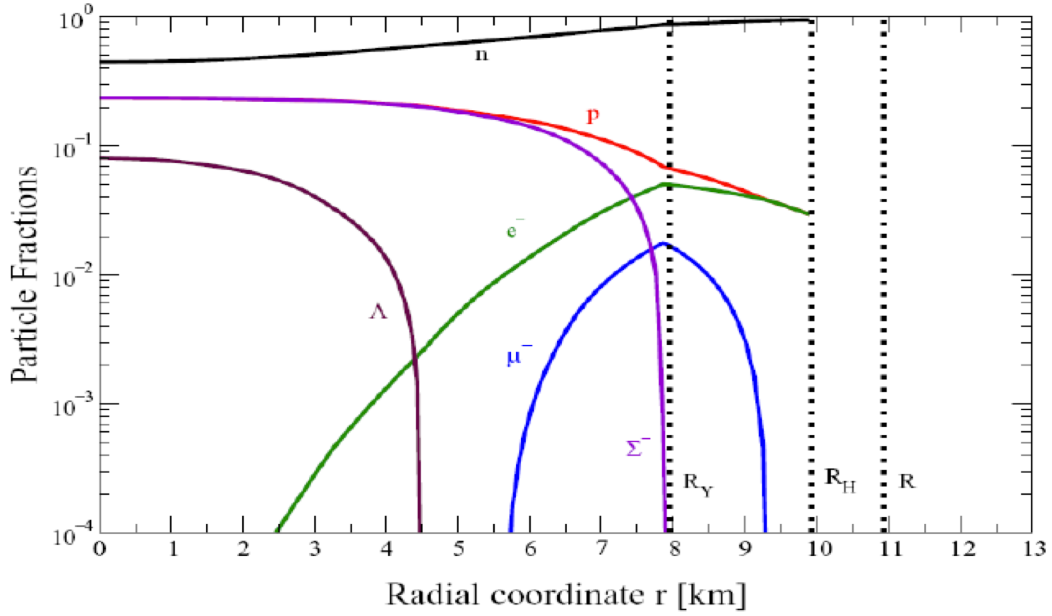
$$n + n \rightarrow p + \Sigma^-$$

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

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

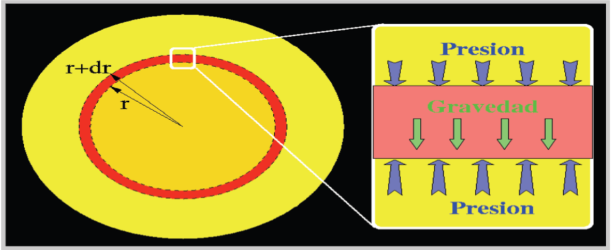
$$\sum_i x_i q_i = 0$$



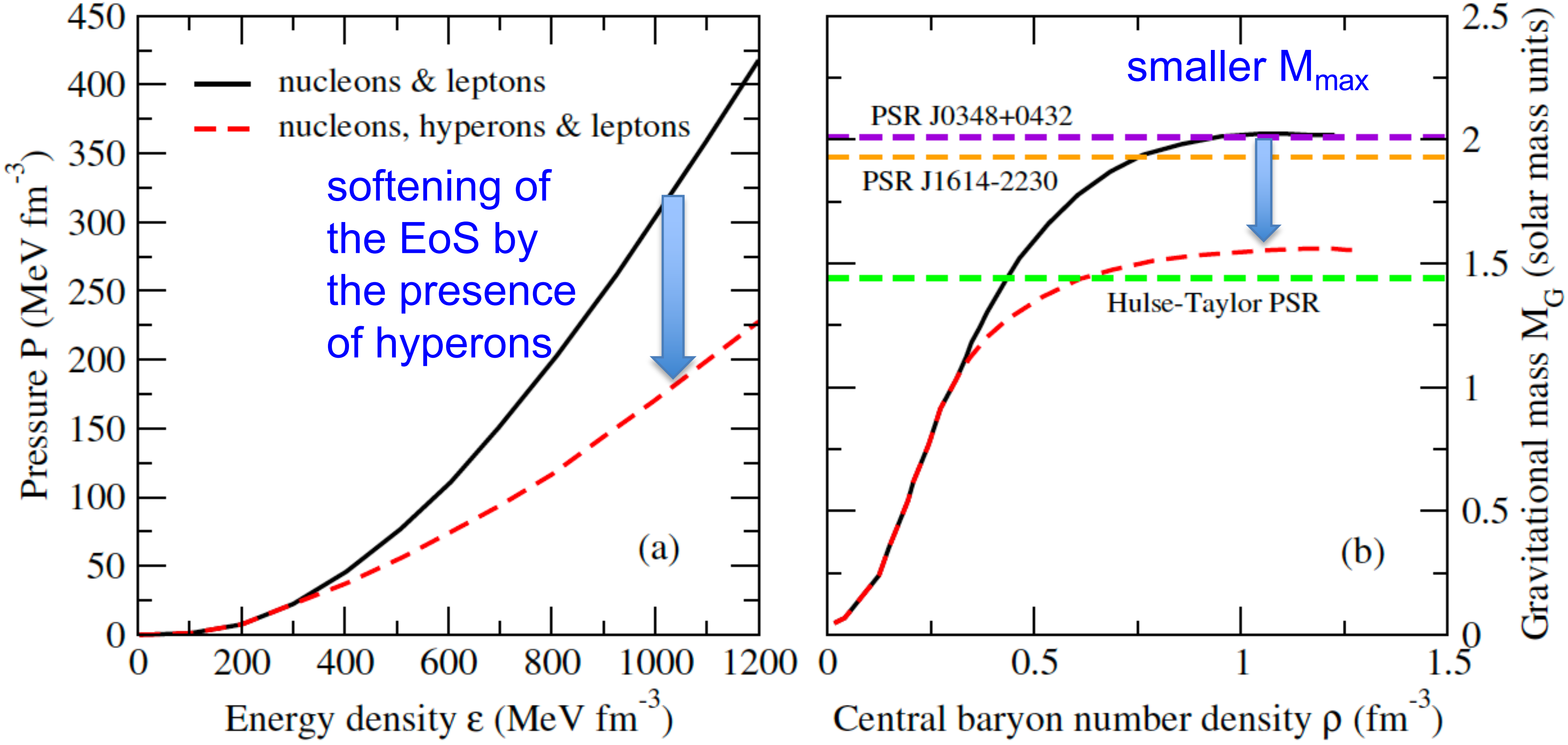


credit: I.Vidana

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

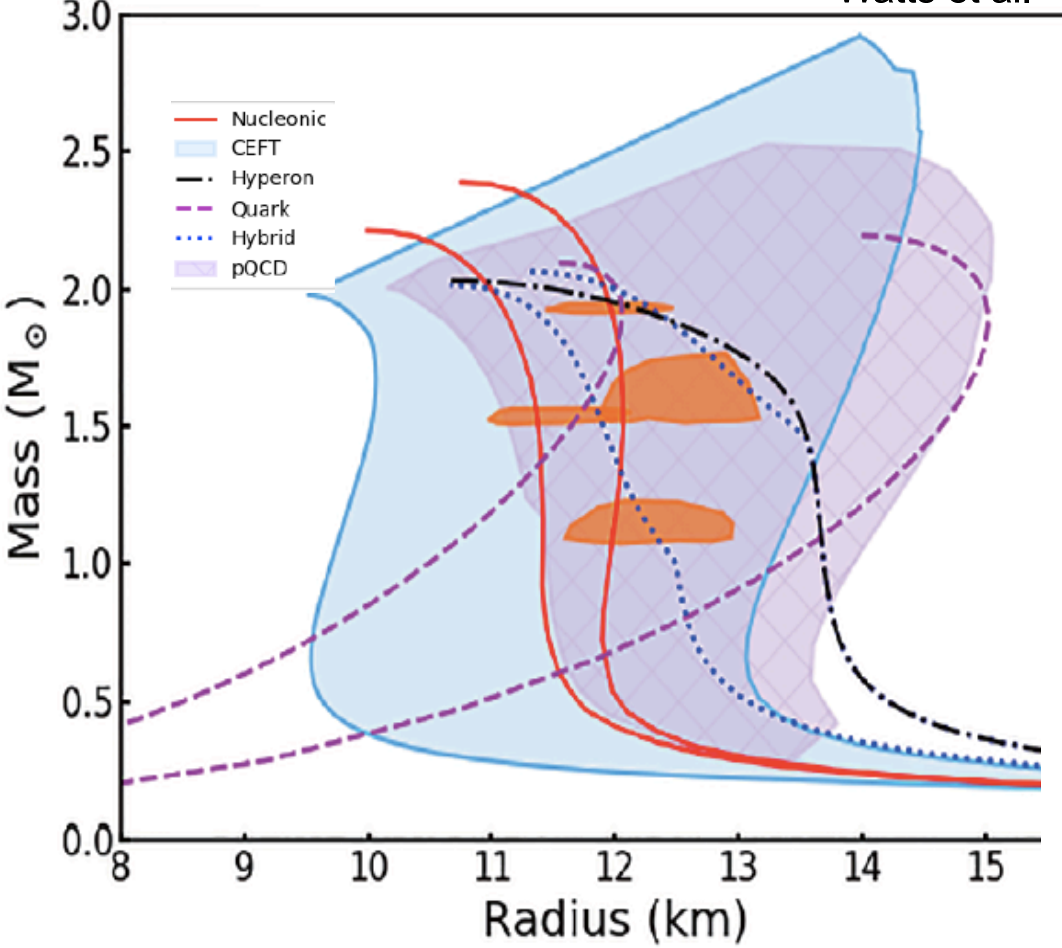
The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to **maximum neutron star masses < $2M_\odot$**

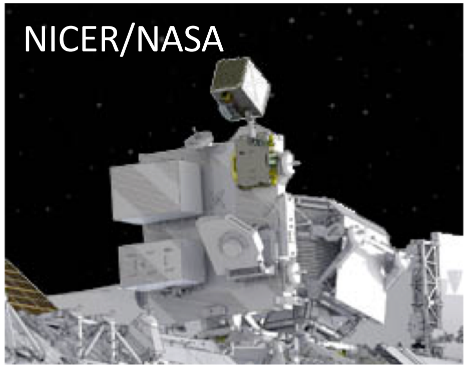
Solution?

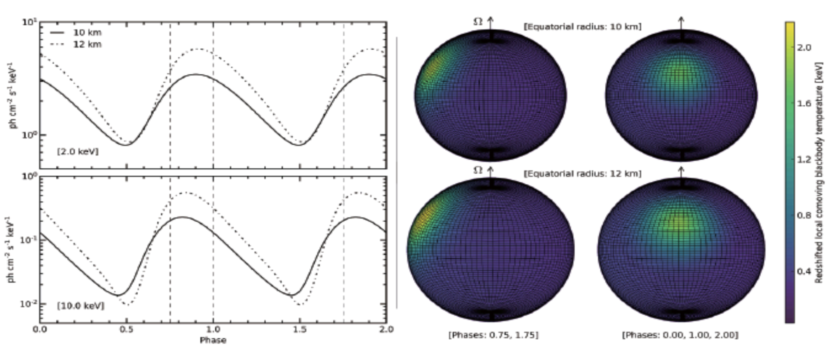
- ➢ **stiffer YN and YY interactions**
- ➢ **hyperonic 3-body forces**
- ➢ push of Y onset by Δ-isobars or meson condensates
- ➢ quark matter below Y onset
- ➢ dark matter, modified gravity theories…

Space missions to study the interior of NS

Watts et al. ‘19

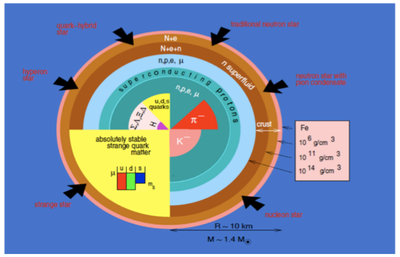




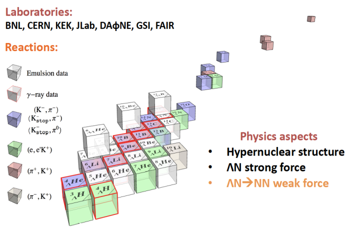


Constraints from pulse profile modelling of rotation-powered pulsars with eXTP

and multimessenger astronomy!



Present and Future


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

Reactions:

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

A lot of experimental and theoretical effort has been invested to understand hyperon-nucleon and hyperon-hyperon interactions

Hyperon-nucleon and hyperon-hyperon interactions are crucial for describing hypernuclei and understanding long-standing problems, such as the hypertriton lifetime puzzle

The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the equation of state that leads to maximum neutron star masses < $2M_\odot$
This is known as The Hyperon Puzzle

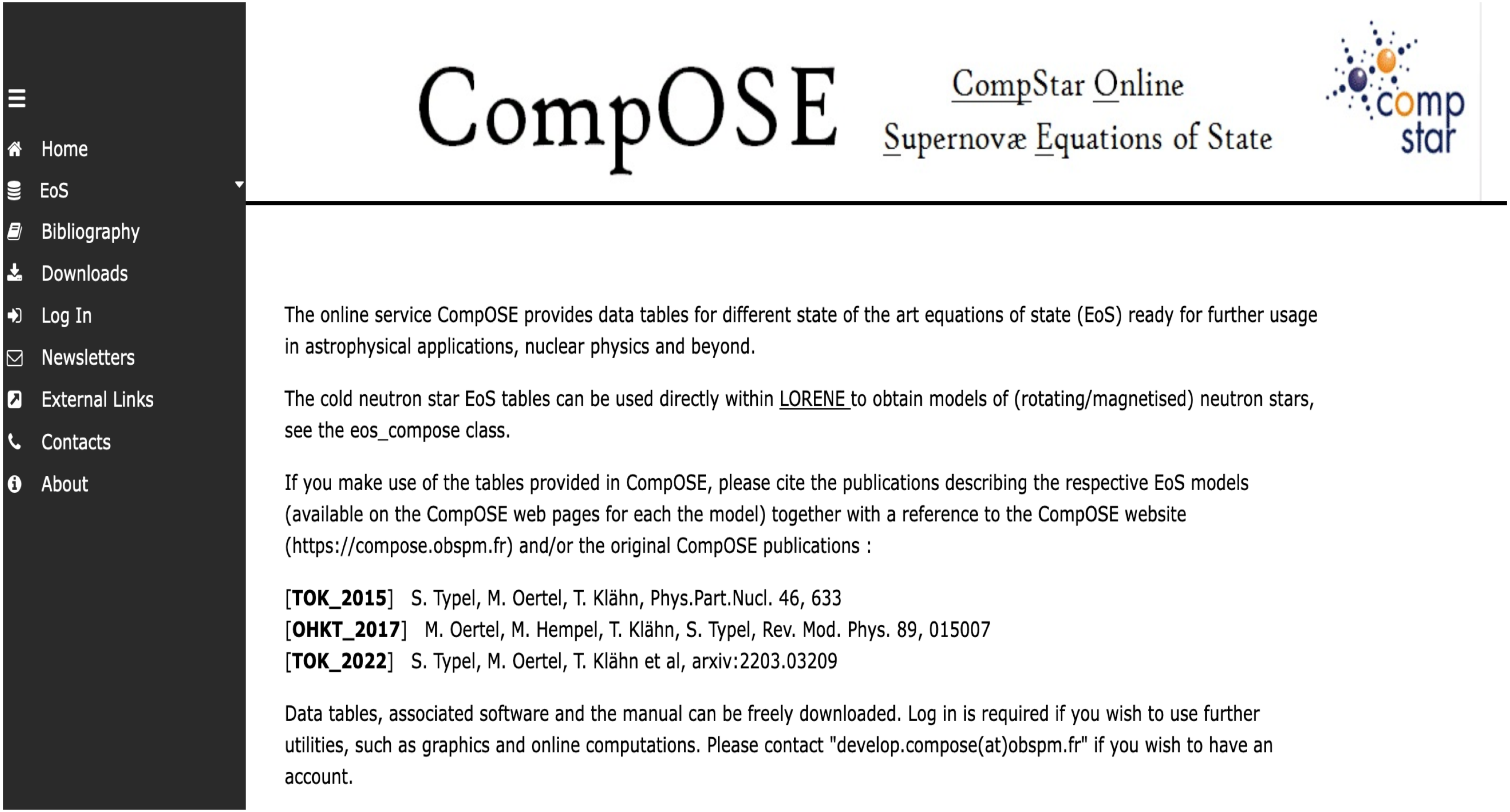
The future of hyperon physics relies on particle and nuclear experiments as well as X-ray and multimessenger astronomy

STRONG 2020

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

https://compose.obspm.fr/



The online service CompOSE provides data tables for different state of the art equations of state (EoS) ready for further usage in astrophysical applications, nuclear physics and beyond.

The cold neutron star EoS tables can be used directly within LORENE to obtain models of (rotating/magnetised) neutron stars, see the eos_compose class.

If you make use of the tables provided in CompOSE, please cite the publications describing the respective EoS models (available on the CompOSE web pages for each the model) together with a reference to the CompOSE website (https://compose.obspm.fr) and/or the original CompOSE publications :

[**TOK_2015**] S. Typel, M. Oertel, T. Klähn, Phys.Part.Nucl. 46, 633
[**OHKT_2017**] M. Oertel, M. Hempel, T. Klähn, S. Typel, Rev. Mod. Phys. 89, 015007
[**TOK_2022**] S. Typel, M. Oertel, T. Klähn et al, arxiv:2203.03209

Data tables, associated software and the manual can be freely downloaded. Log in is required if you wish to use further utilities, such as graphics and online computations. Please contact "develop.compose(at)obspm.fr" if you wish to have an account.

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