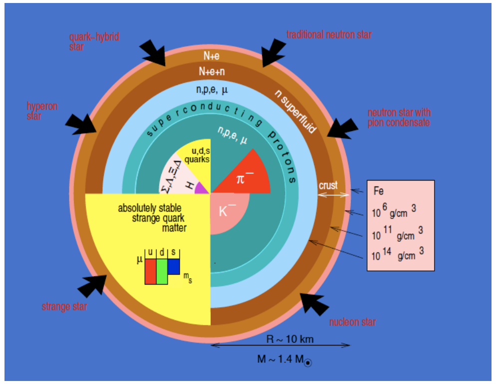
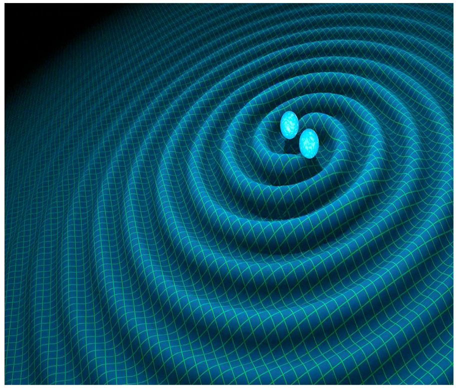




Hyperons in Neutron Stars and Mergers

Institute of Space Sciences

CSIC Consejo Superior de Investigaciones Científicas

IEEC

Laura Tolós

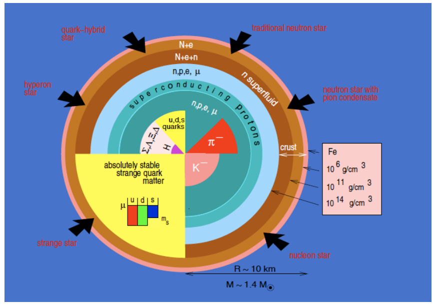
FIAS Frankfurt Institute for Advanced Studies

Svenskt kärnfysikermöte 2024

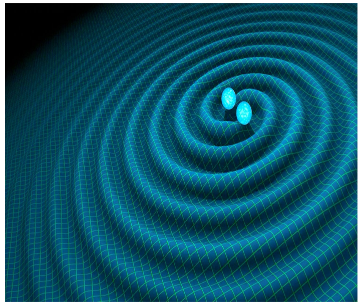
30 October 2024 to 1 November 2024

Fysicum

UTC timezone



Outline



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

Hyperons and where to find them

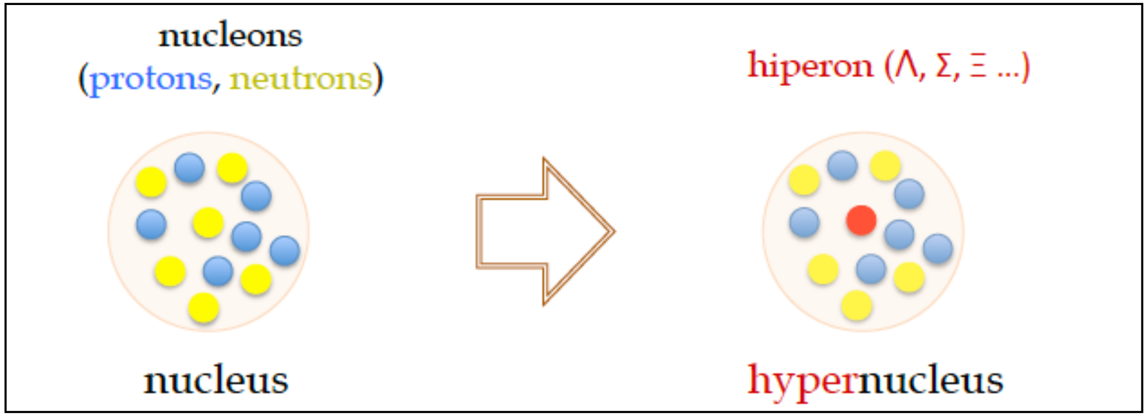
A hyperon is a baryon containing one or more strange quarks

Baryon	$I(J^P)$	Mass [MeV]	Quark Content
p	$1/2(1/2^+)$	938.27	uud
n	$1/2(1/2^+)$	939.56	udd
Λ	$0(1/2^+)$	1115.68	uds
Σ^+	$1(1/2^+)$	1189.37	uus
Σ^0	$1(1/2^+)$	1192.64	uds
Σ^-	$1(1/2^+)$	1197.45	dds
Ξ^0	$1/2(1/2^+)$	1314.86	uss
Ξ^-	$1/2(1/2^+)$	1321.71	dss
Ω^-	$0(3/2^+)$	1672.45	sss

The study of hypernucleus allows for

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

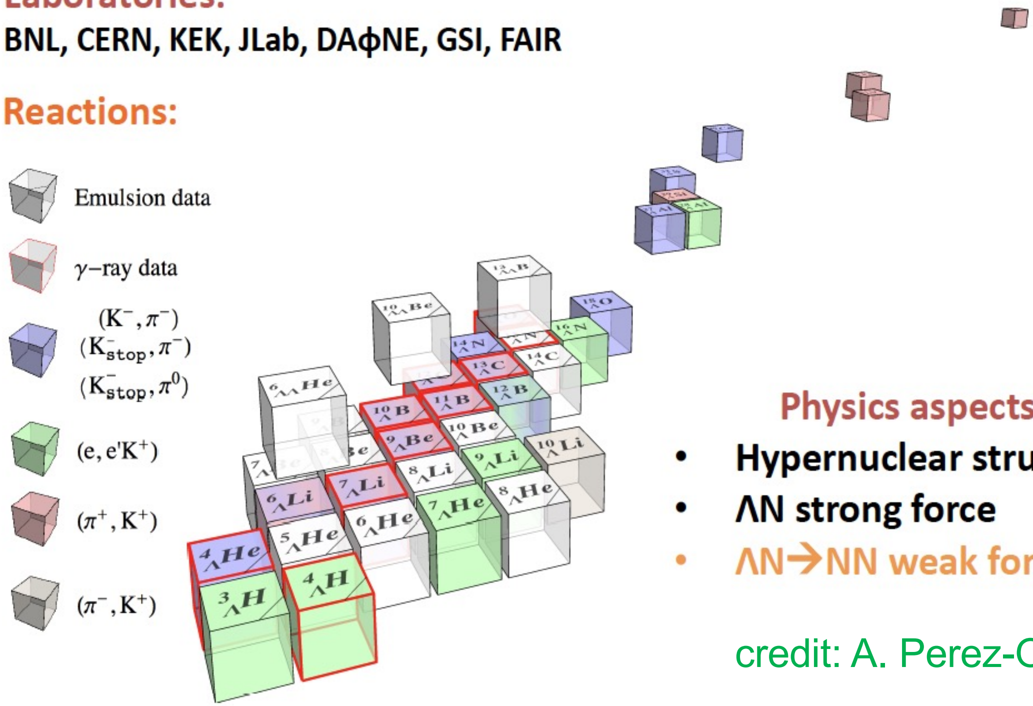
On Earth: Hypernuclei



credit: A. Parreno

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

Reactions:

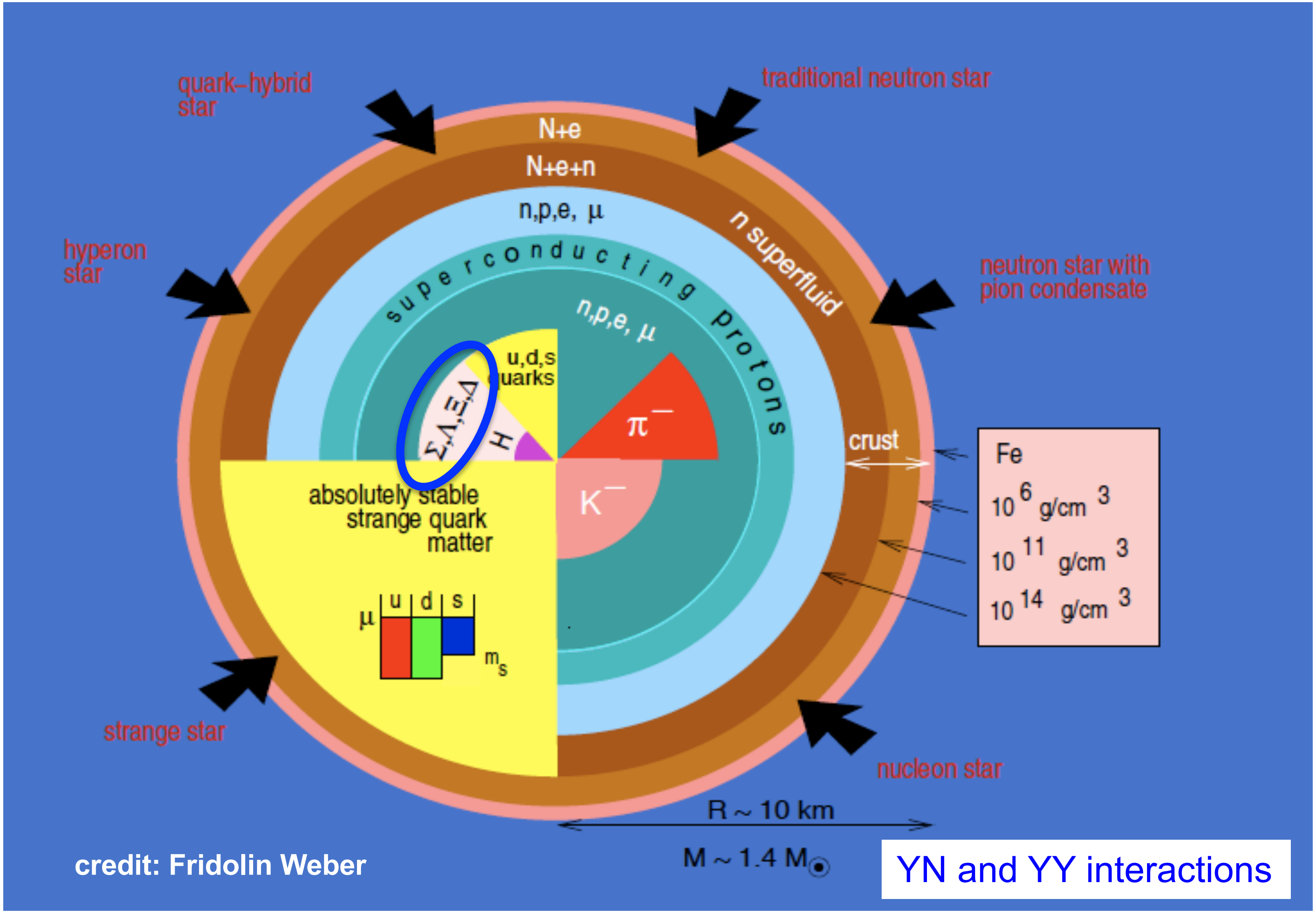


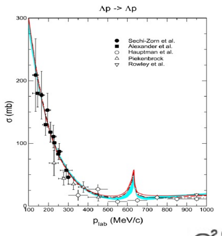
Physics aspects

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

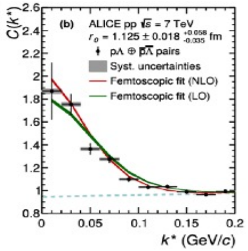
credit: A. Perez-Obiol

In Neutron Stars

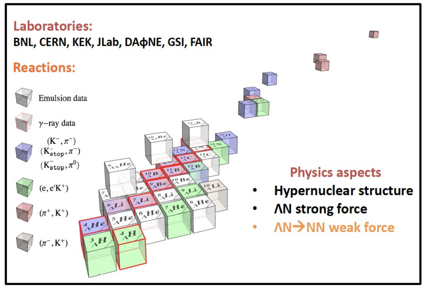




YN and YY interactions



- 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 $SU(3)_{flavor}$ 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

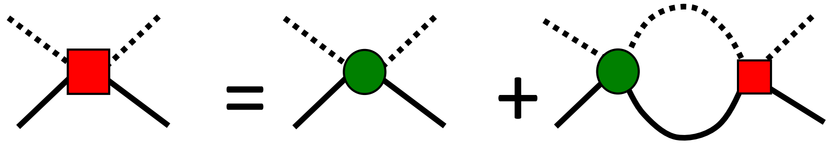
Schaefer, Wagner, Wambach, Kuo and Brown '06

- Lattice calculations (HALQCD/NPLQCD/BaSc)

To solve YN and YY interactions on the lattice

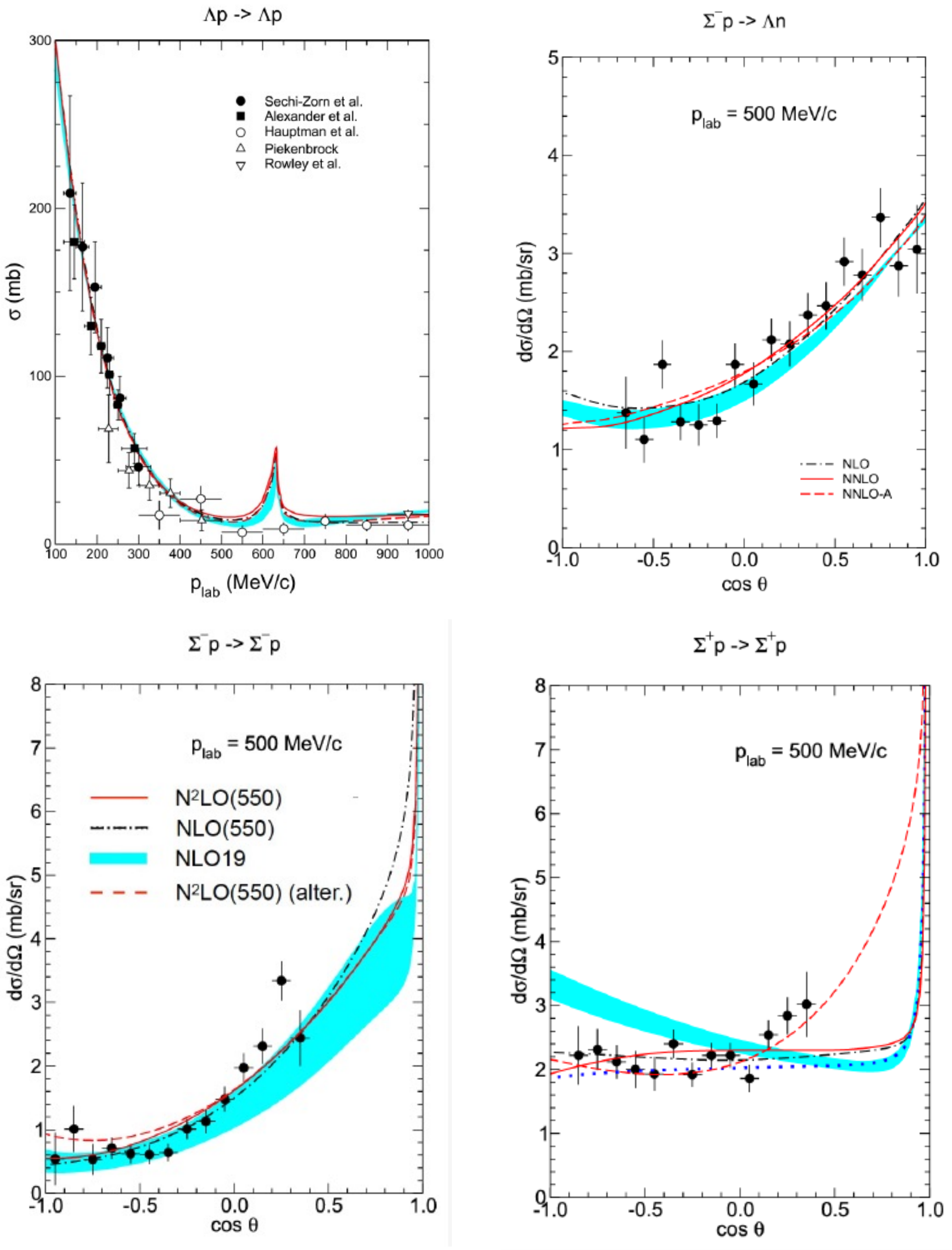
HALQCD: Ishii, Aoki, Hatsuda '07; Aoki, Hatsuda and Ishii '10; Aoki et al '12
NPLQCD: Beane, Orginos and Savage '11; Beane et al '12

YN scattering



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

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

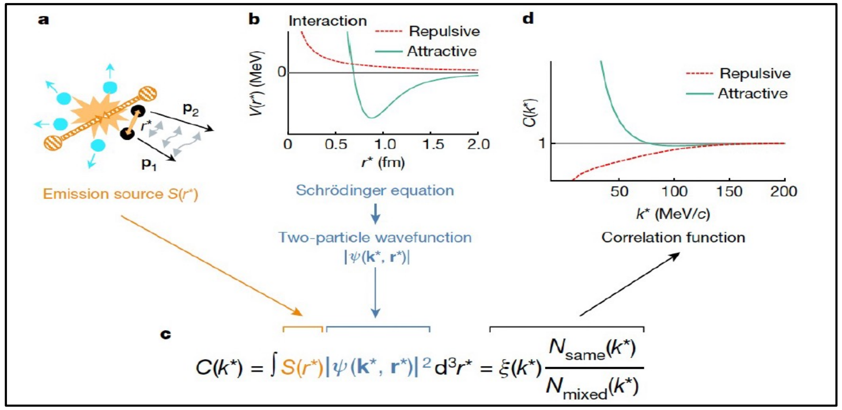


latest data on YN scattering
using new data
from J-PARC and CLAS

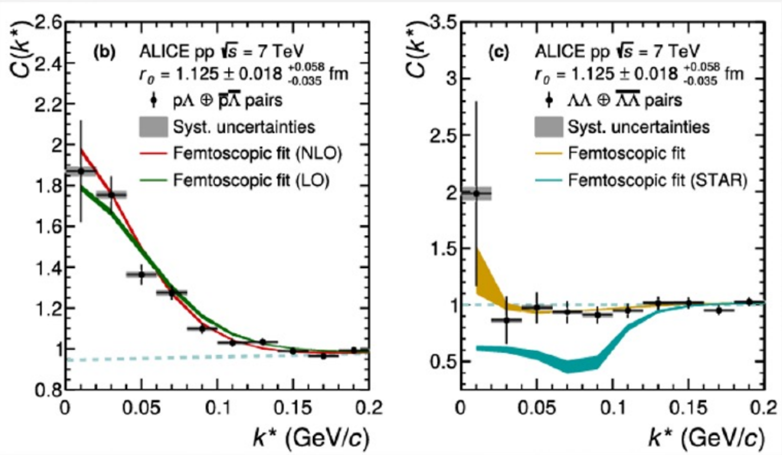
Haidenbauer, Meißner, Nogga and Le ‘23

Femtoscopy (ALICE@LHC)

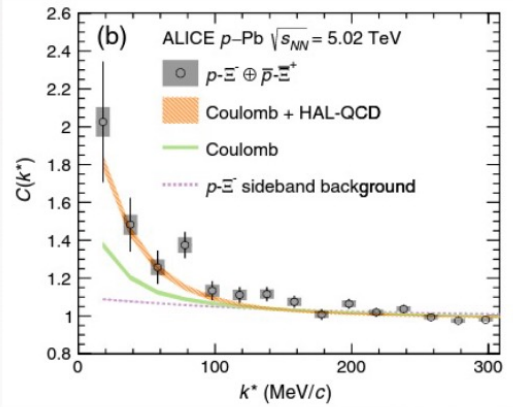
ALICE Collaboration, Nature 588 (2020) 232
Fabbietti, Mantovani-Sarti, Vazquez-Doce ‘21



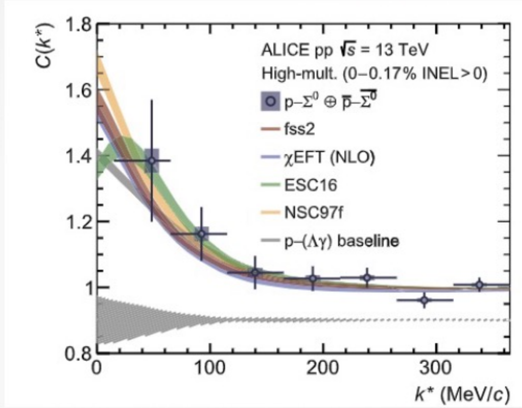
ALICE, PRC (2019)



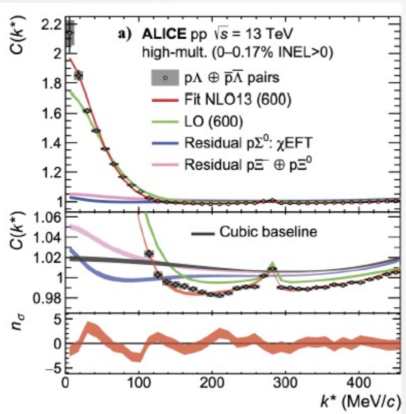
ALICE, PRL (2019)



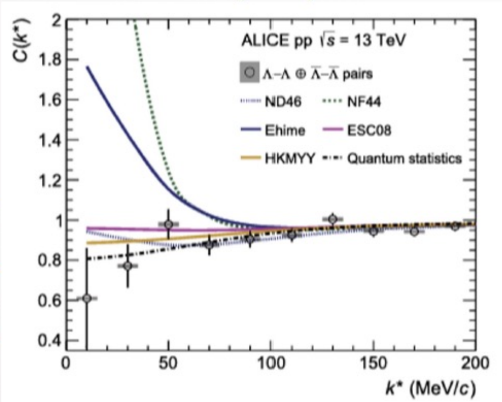
ALICE, PLB (2020)



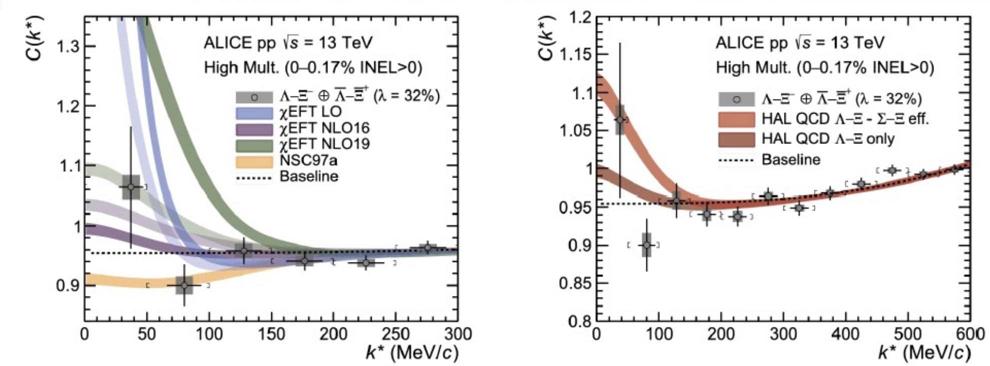
ALICE, PLB (2022)



ALICE, PLB (2019)

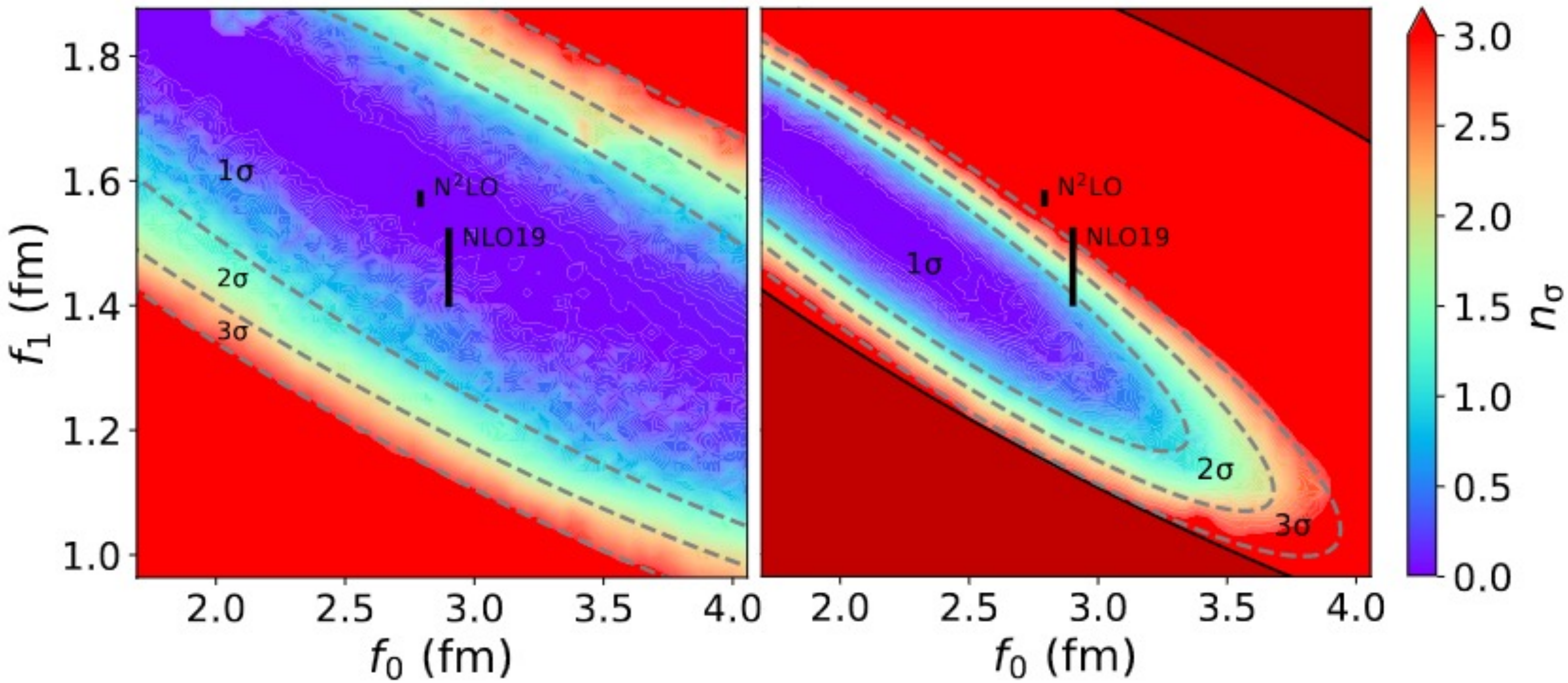


ALICE, PLB (2023)



credit: A. Ramos

First combined analysis of low-energy femtoscopic and scattering data to constrain the s-wave scattering parameters of the Λp interaction



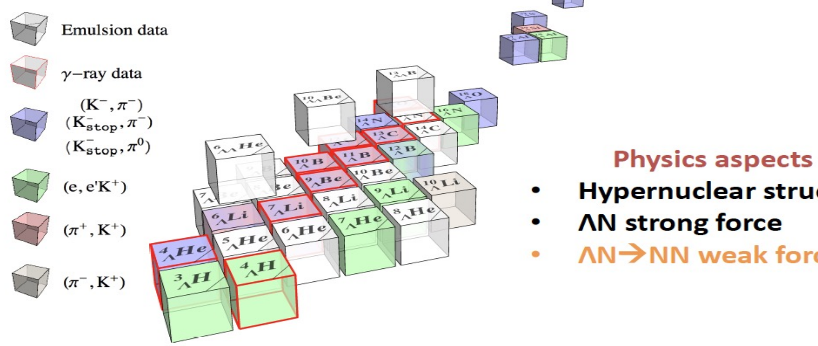
Λp interaction is overall less attractive!

Mihaylov, Haidenbauer and Mantovani-Sarti '24

Hypernuclei

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

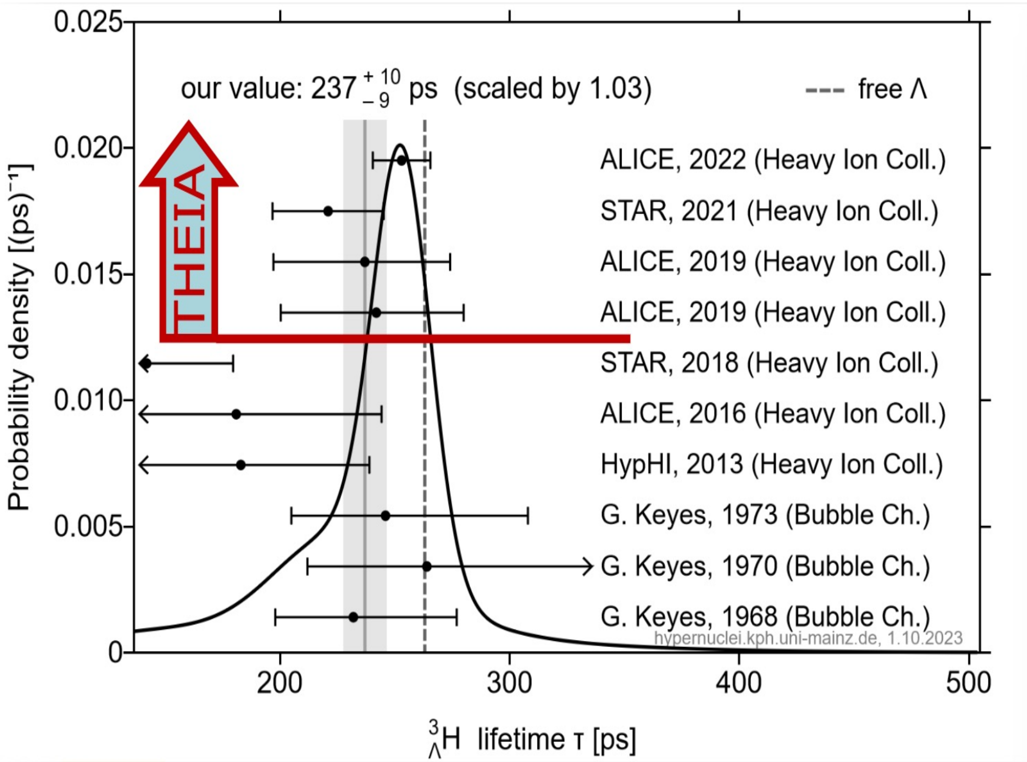
Reactions:



Physics aspects

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

Hypertriton lifetime puzzle



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

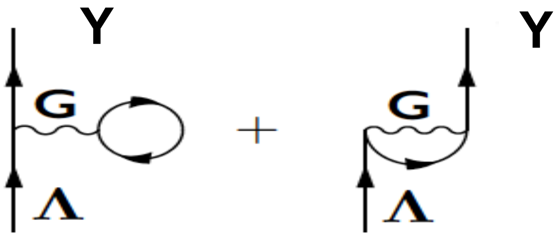
⇔ observed: $\tau(^3_\Lambda H) < \tau(\Lambda)$

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

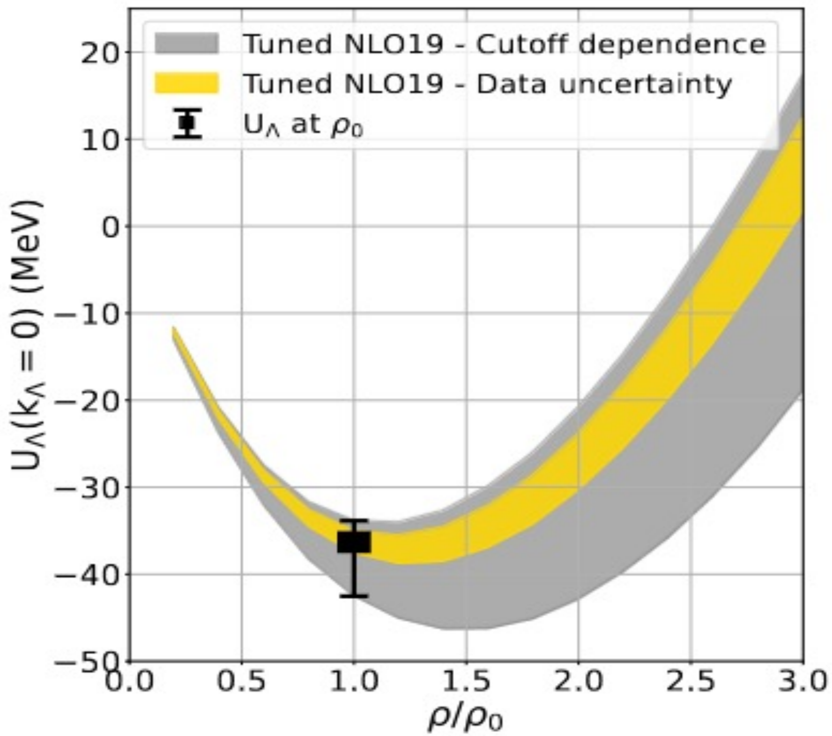
Λ in dense matter



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

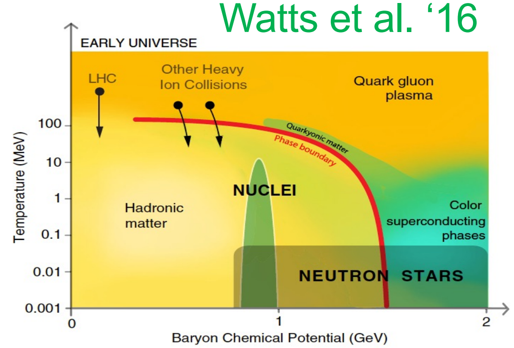
with new parametrization from combined analysis of scattering data and correlation functions

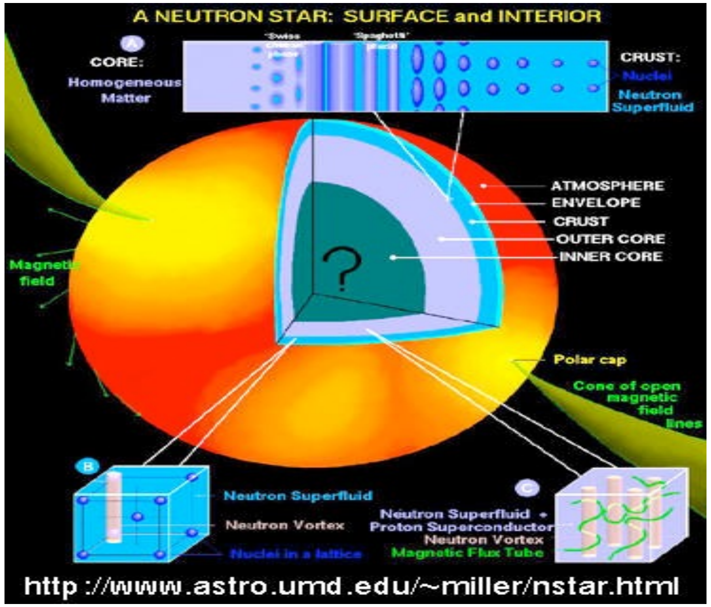
Mihaylov, Haidenbauer and Mantovani-Sarti ‘24

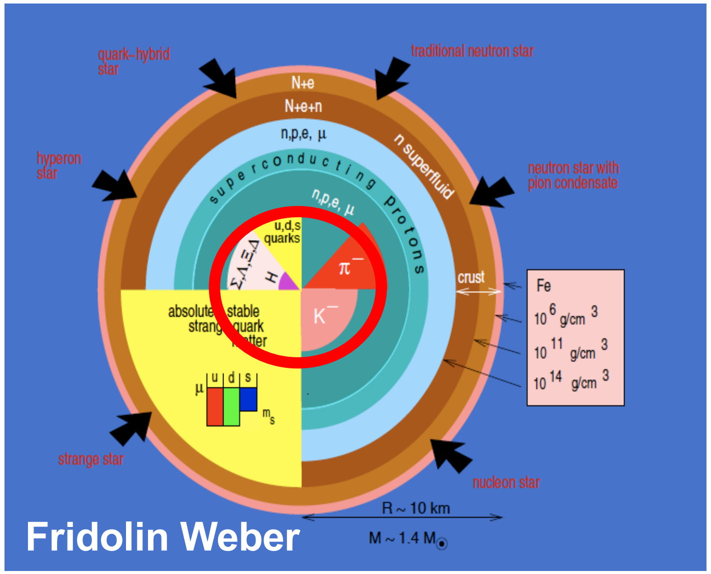


Hyperons and Neutron Stars

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

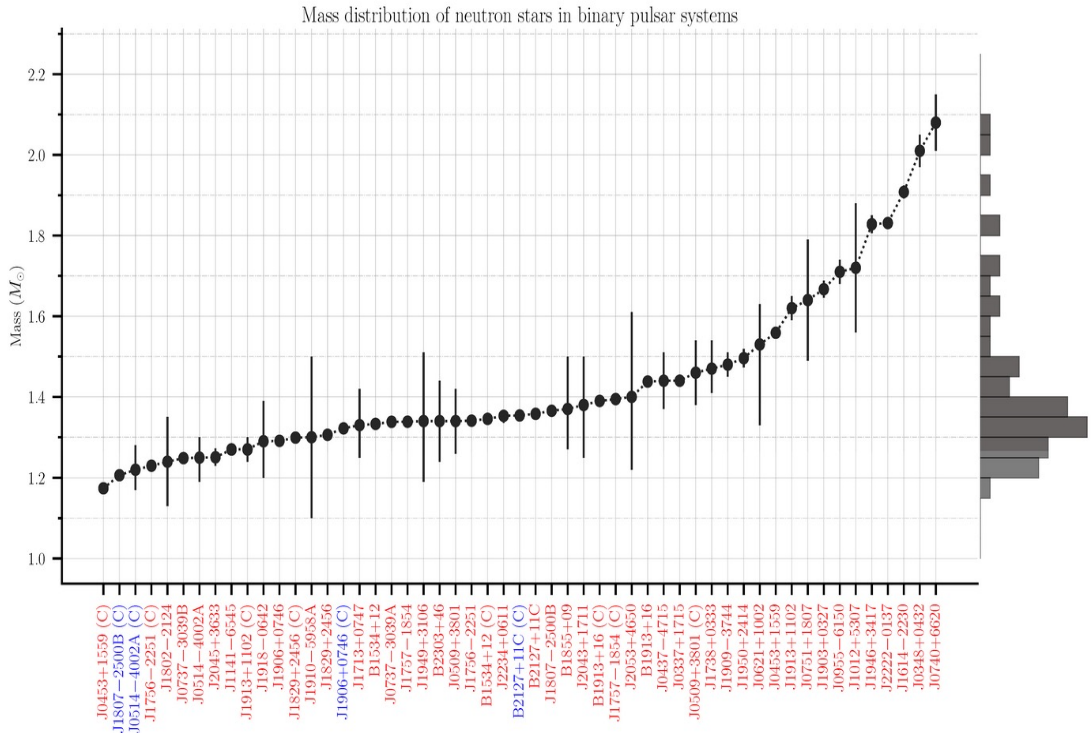
- magnetic field : $B \sim 10^{8..16}$ G

- temperature: $T \sim 10^{6\ldots11}$ K

- observations: masses, radius, gravitational waves…

Masses

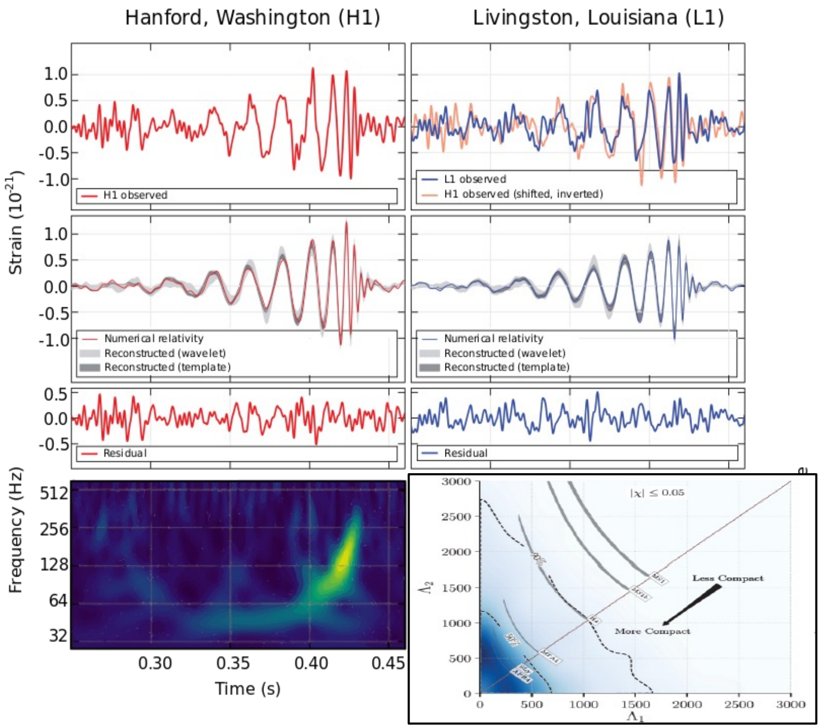
credit: P. Freire



Observations

GW170817

Abbot et al. (LIGO-VIRGO) ’17 ’18



..also GW190425, GW190814

Radius

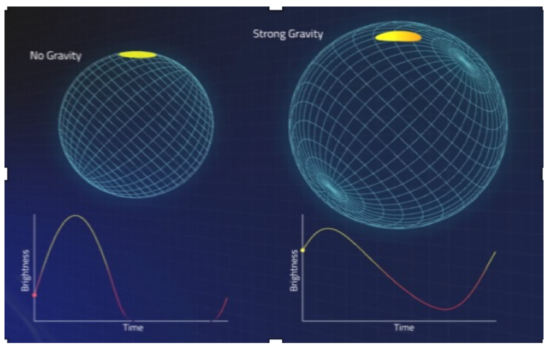
NICER

X-rays from
hot spots
at the surface of
rotating neutron stars

PSR J0030+0451

PSR J0740+6620

PSR J0437-4715



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

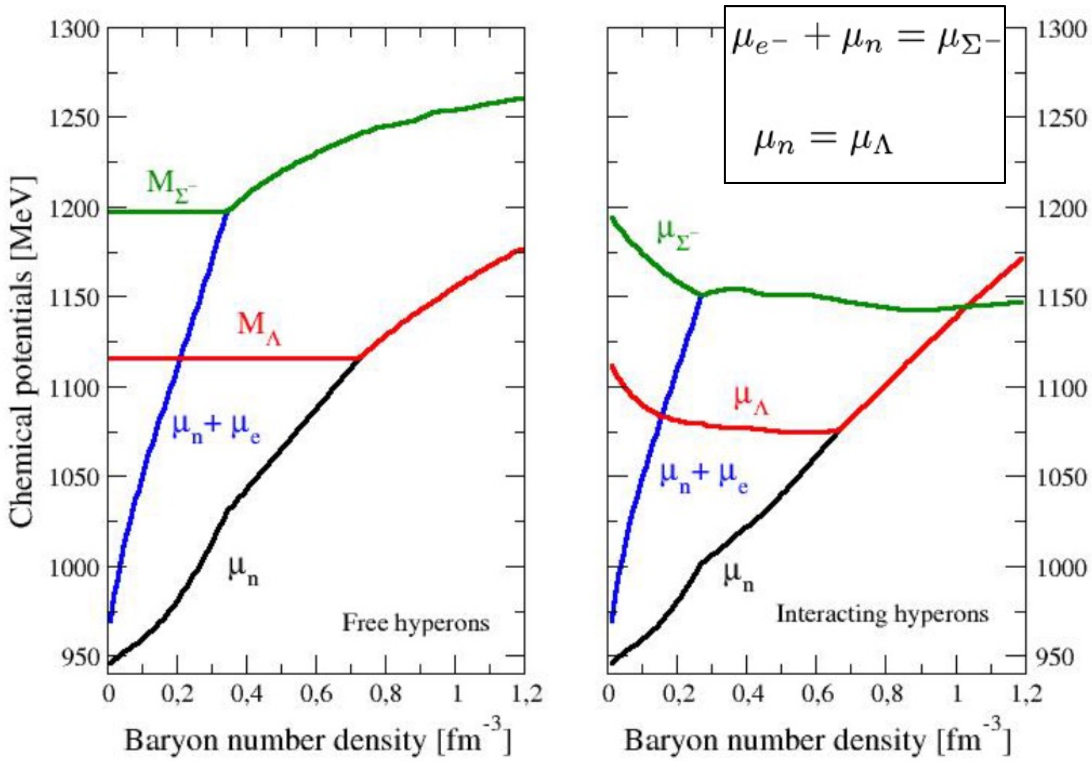
Hyperons might be present at $n \sim (2\text{-}3)n_0$!!!

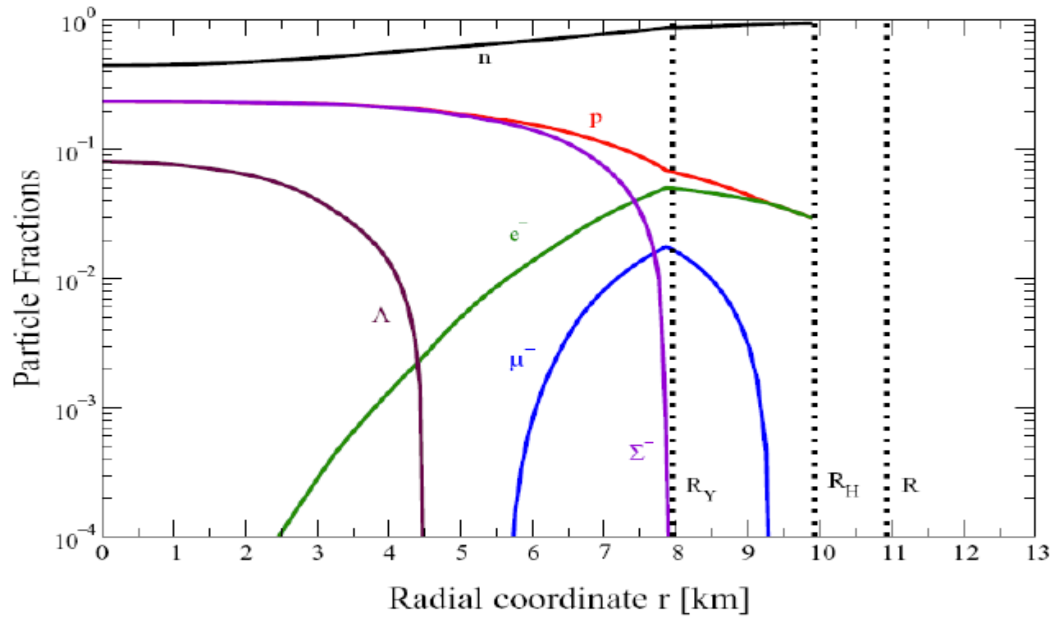
β-stable hyperonic matter

μ_N is large enough to make N->Y favorable

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

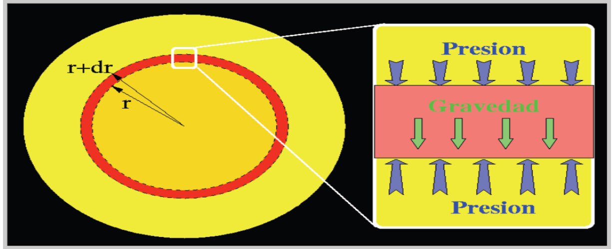
$$\mu_i = b_i \mu_n - q_i \mu_e$$
$$\sum_i x_i q_i = 0$$



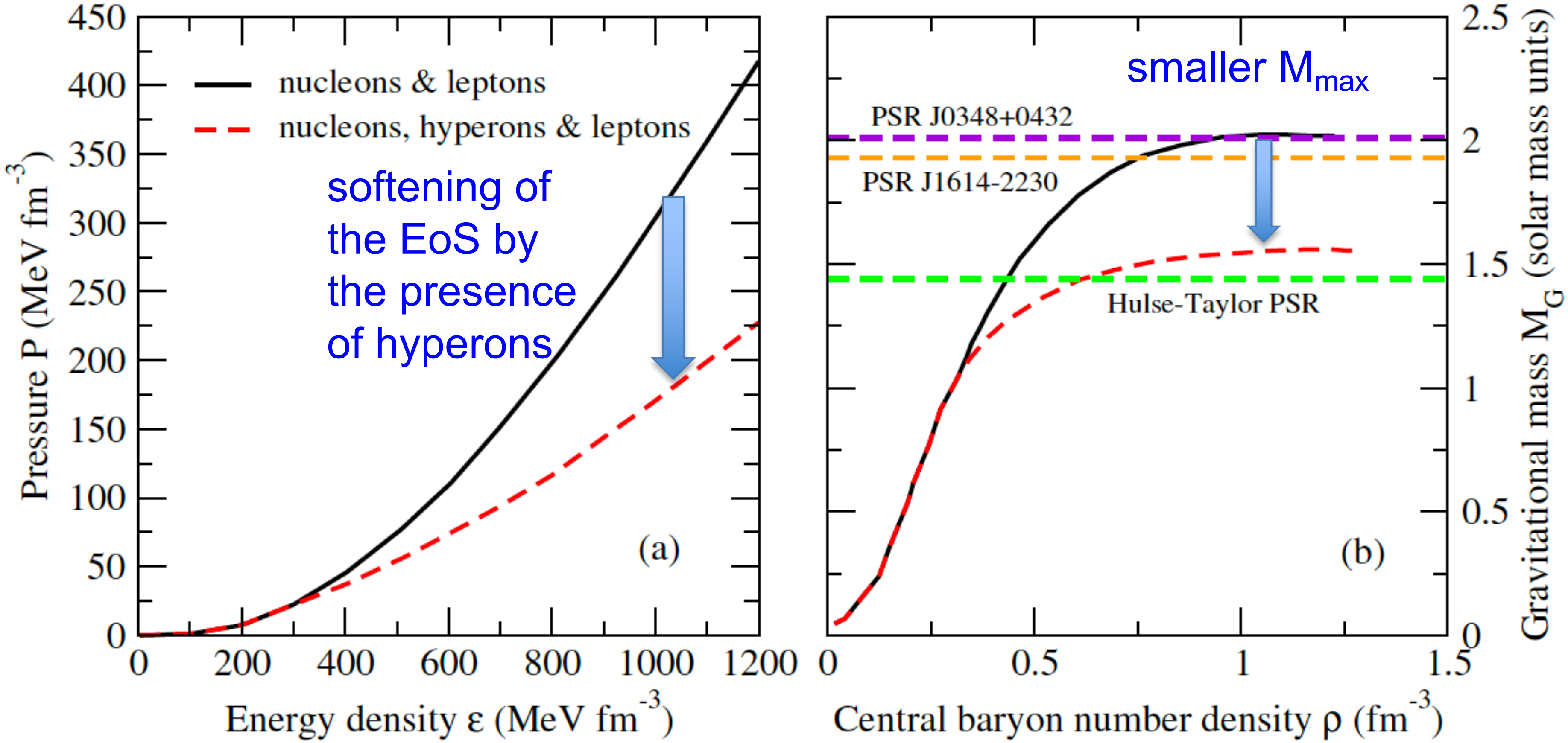


credit: I.Vidana

Inclusion of hyperons….



credit:
Dani P. Page



….. 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 (but improving) 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 < $2M_{\odot}$**

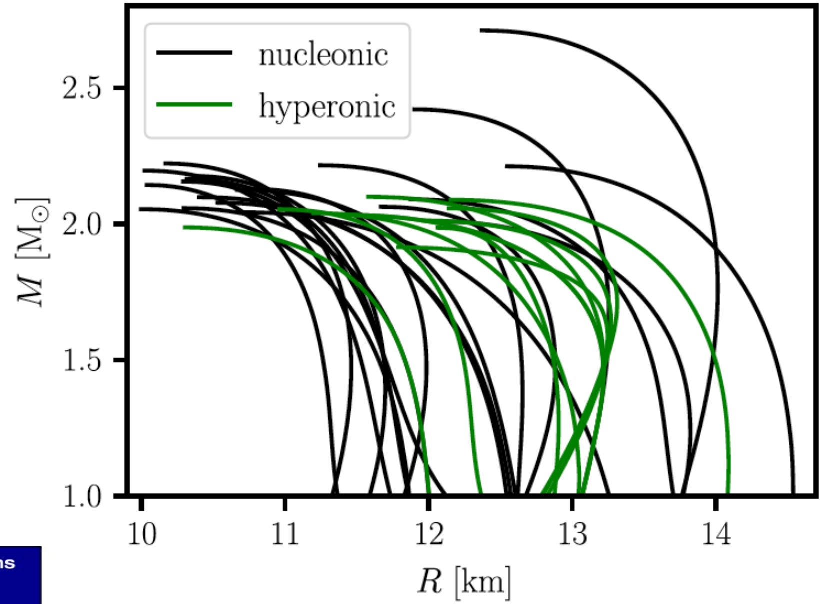
Solution?

- **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…

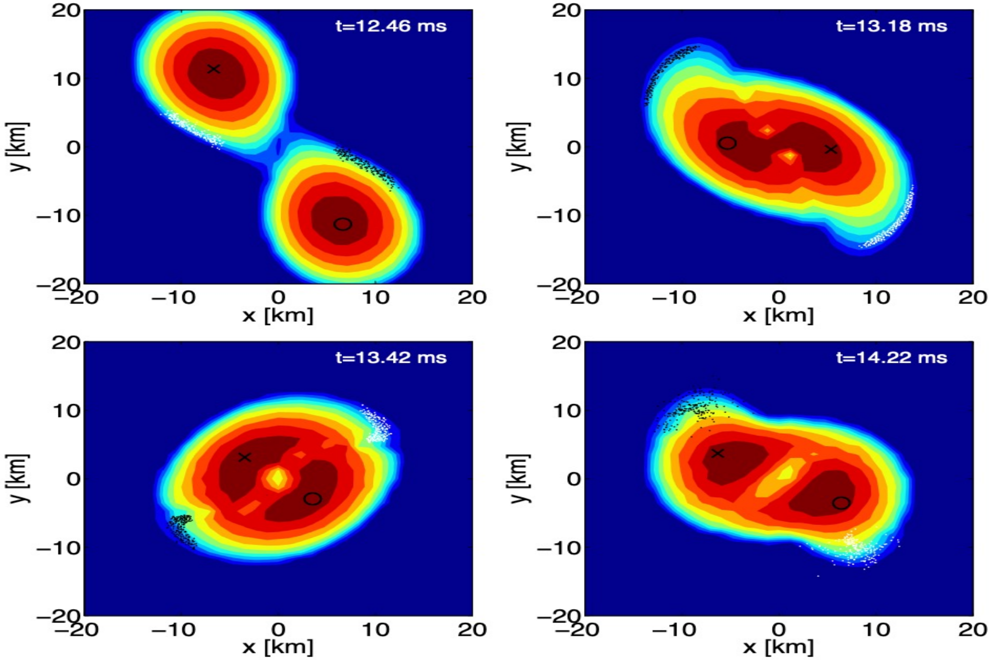
Neutron Star Mergers

Blacker, Kochankovski, Bauswein, Ramos and LT '24

is there a clear signal of the presence of hyperons in neutron stars?



Bauswein and Stergioulas '15



need of new venues to search for strangeness

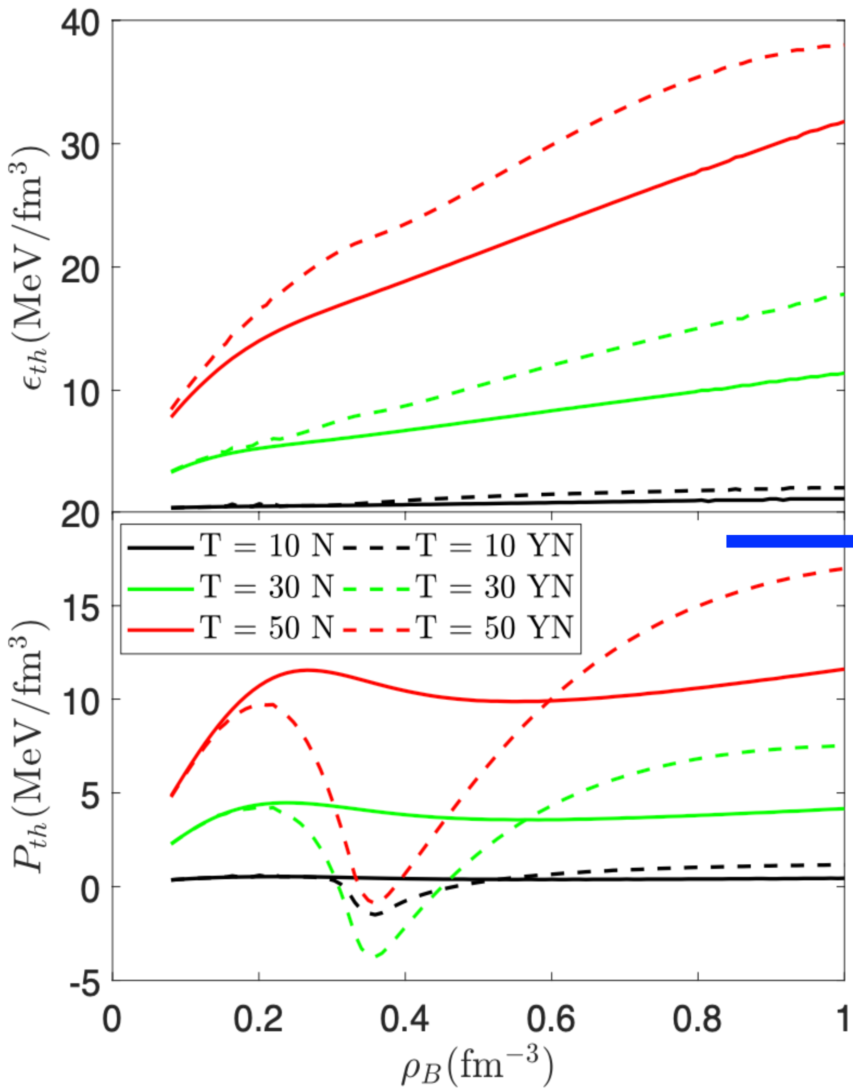
what about mergers?

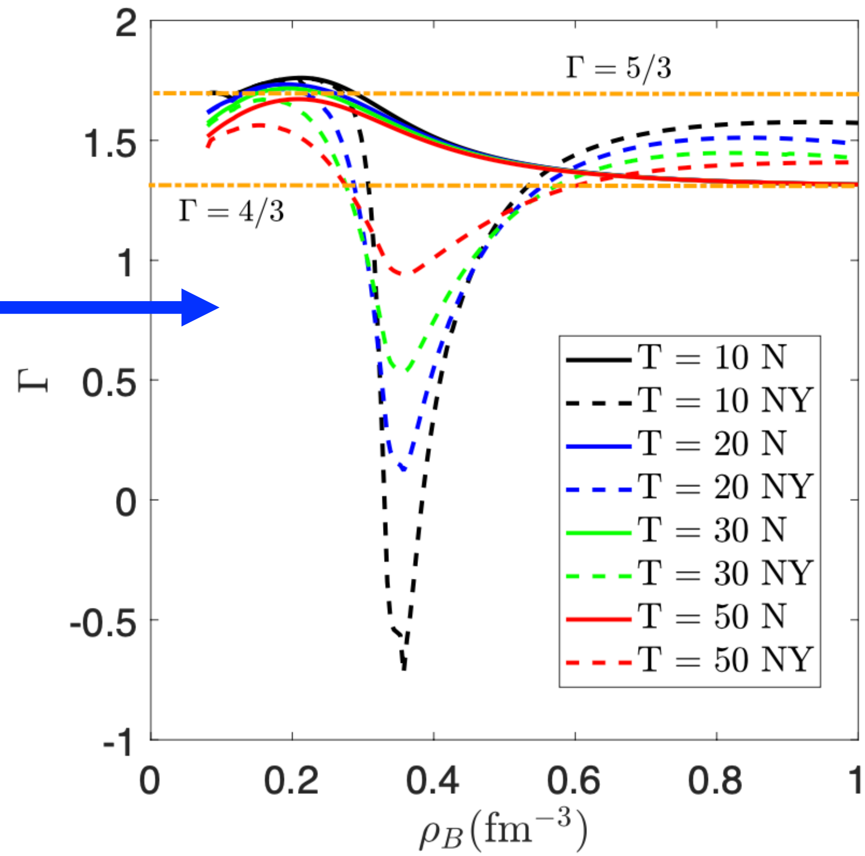
Sekiguchi, Kiuchi, Kyutoku and Shibata '11
Radice, Bernuzzi, Del Pozzo, Robert and Ott '17

check the thermal behaviour!!!

$$\Gamma(\rho_B, T) \equiv 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}}$$

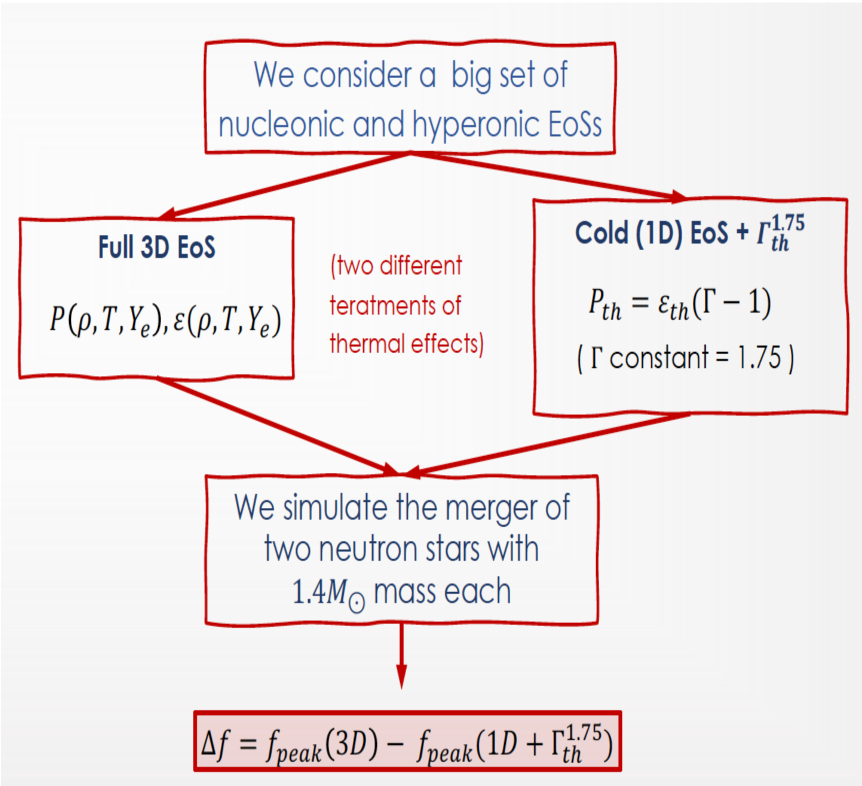
$$P_{\rm th} = P(\rho_B, T) - P(\rho_B, T=0)$$
$$\epsilon_{\rm th} = \epsilon(\rho_B, T) - \epsilon(\rho_B, T=0)$$



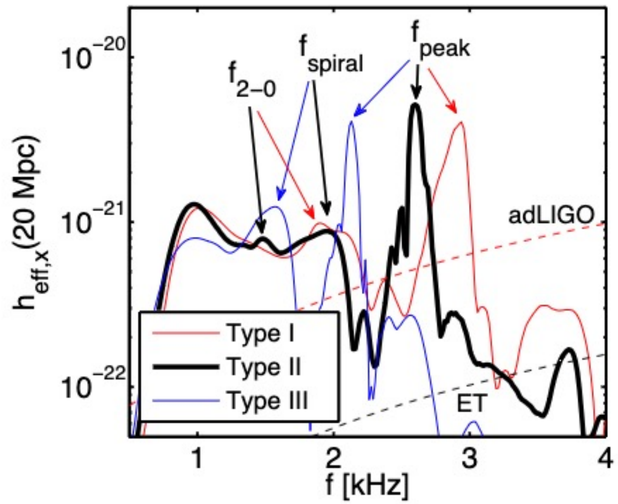


Kochankovski, Ramos and LT ‘22

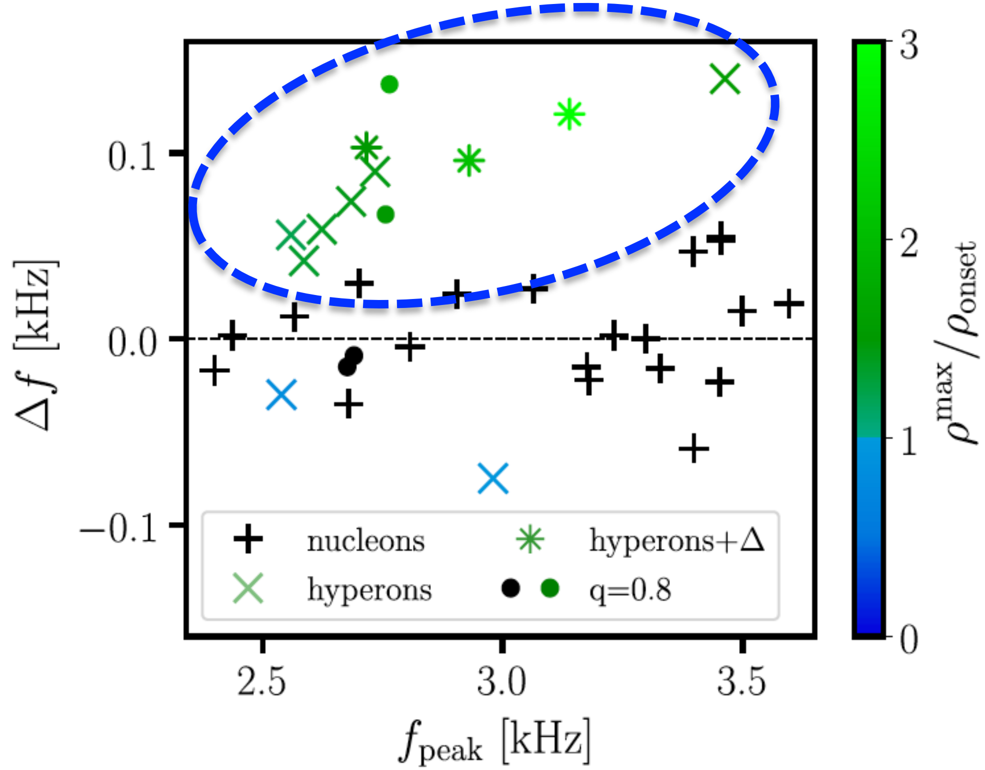
check the thermal behaviour!!!



Bauswein and Stergioulas ‘15



Blacker, Kochankovski, Bauswein, Ramos and LT ‘24

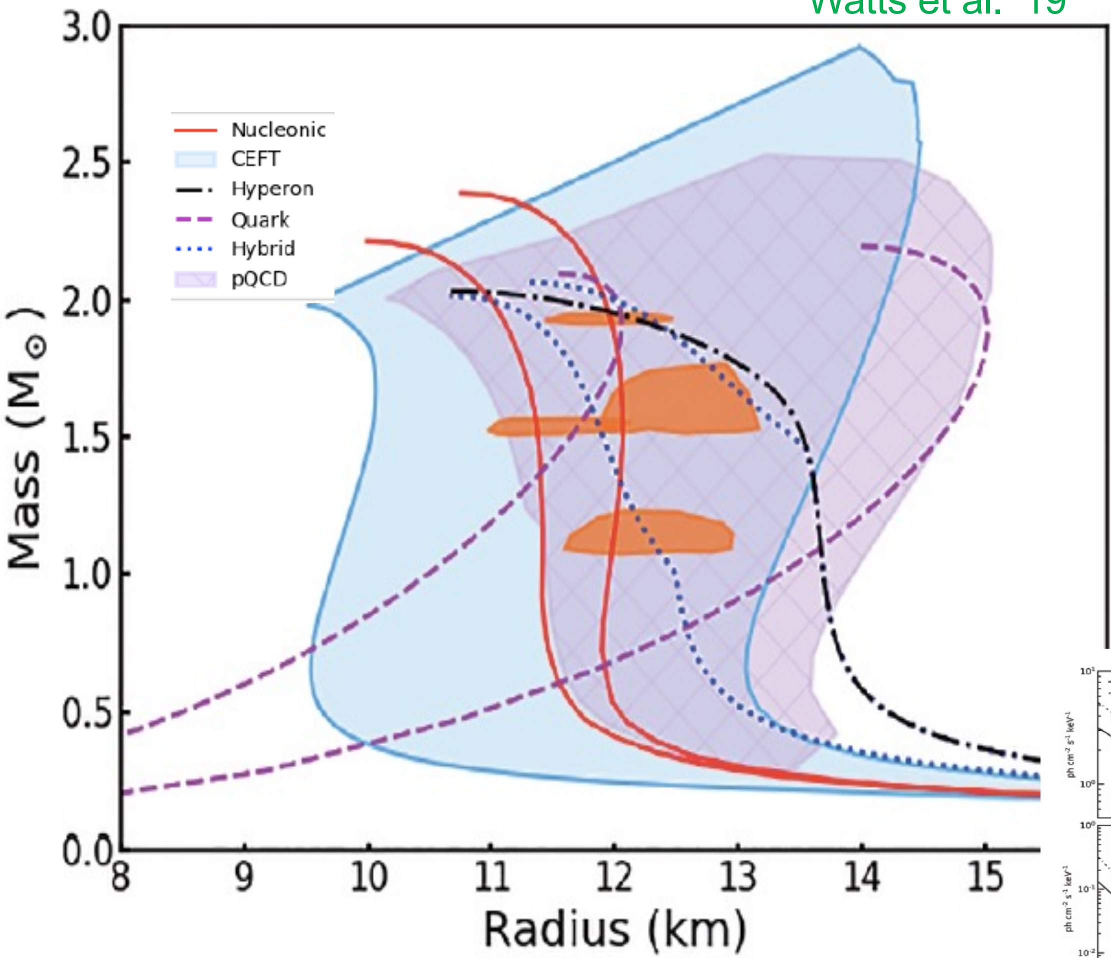


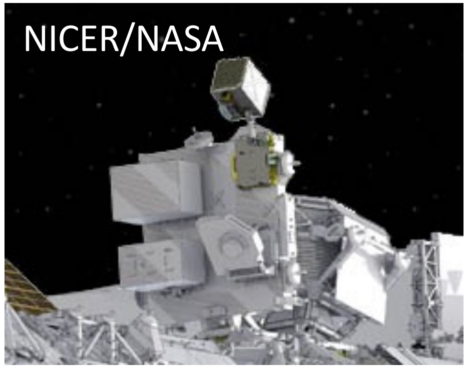
conclusion

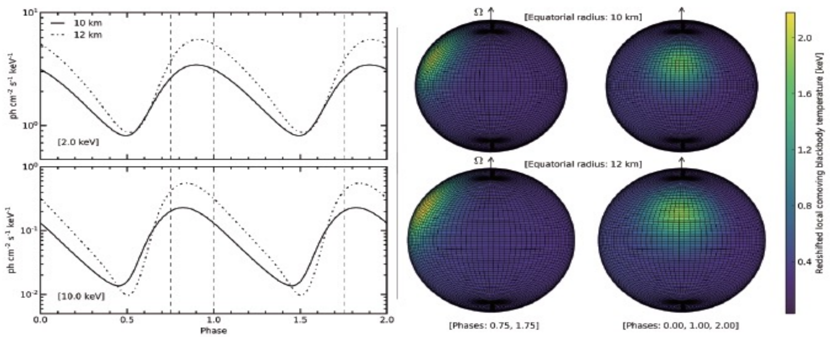
hyperonic models lead to systematically higher frequencies by up to Δf ~ 150 Hz, being small but potentially sizeable

Space missions to study the interior of NS

Watts et al. '19

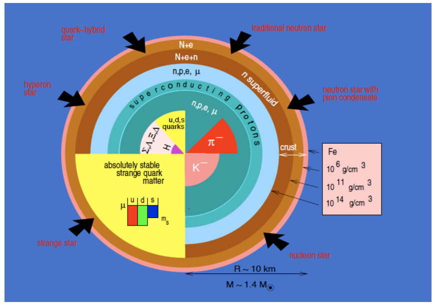




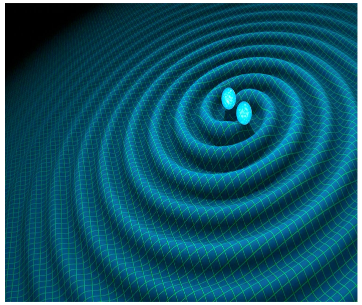


constraints from pulse profile modelling of
rotation-powered pulsars with eXTP

and multimessenger astronomy!



Present and Future



A lot of theoretical and experimental (scattering, femtoscopy, hypernuclei) effort has been invested to understand hyperon-nucleon and hyperon-hyperon interactions

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.

Need of new routes to search for strangeness: neutron star mergers?

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

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CompStar Online
Supernovæ Equations of State

comp star

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.

S. Typel, M. Oertel, T. Klaehn, D. Chatterjee, V. Dexheimer, C. Ishizuka, M. Mancini, J. Novak, H. Pais, C.Providencia, A. Raduta, M. Servillat and L. Tolos
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