Hyperons and Strange Mesons in Nuclei and Neutron Stars

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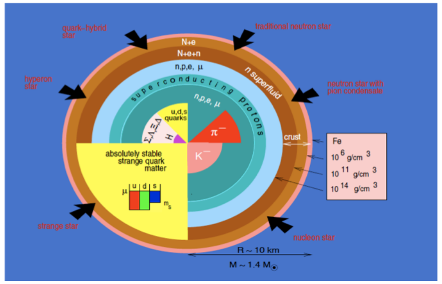
based on

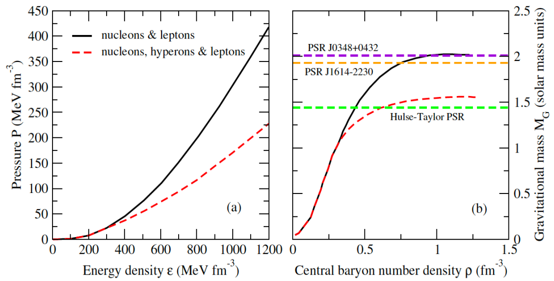
L. Tolos and L. Fabbietti, Prog. Part. Nucl. Phys. 112 (2020) 103770

EMMI Workshop "Meson and Hyperon Interactions with Nuclei"

14-16 September 2022
Kitzbühel, Austria
Europe/Berlin timezone



Hyperons



- 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

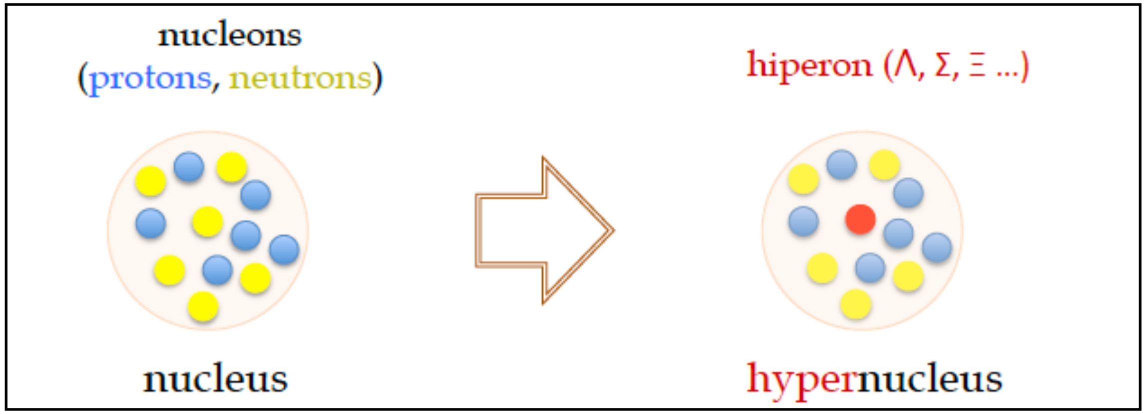
Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

credit: Vidana

The study of hypernucleus allows for

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

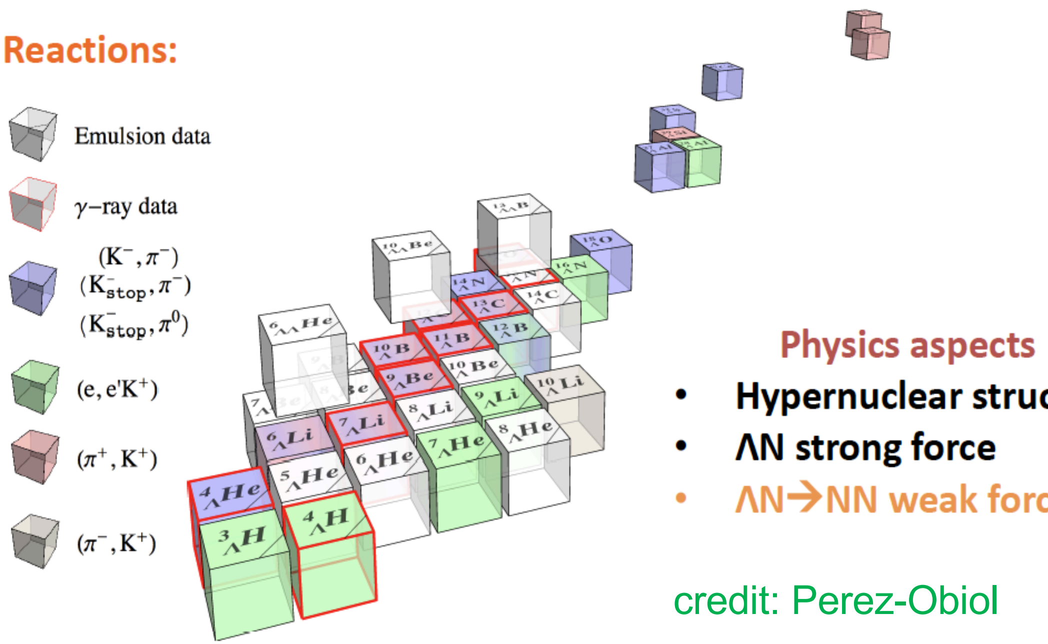
On Earth: Hypernuclei



credit: Parreno

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

Reactions:

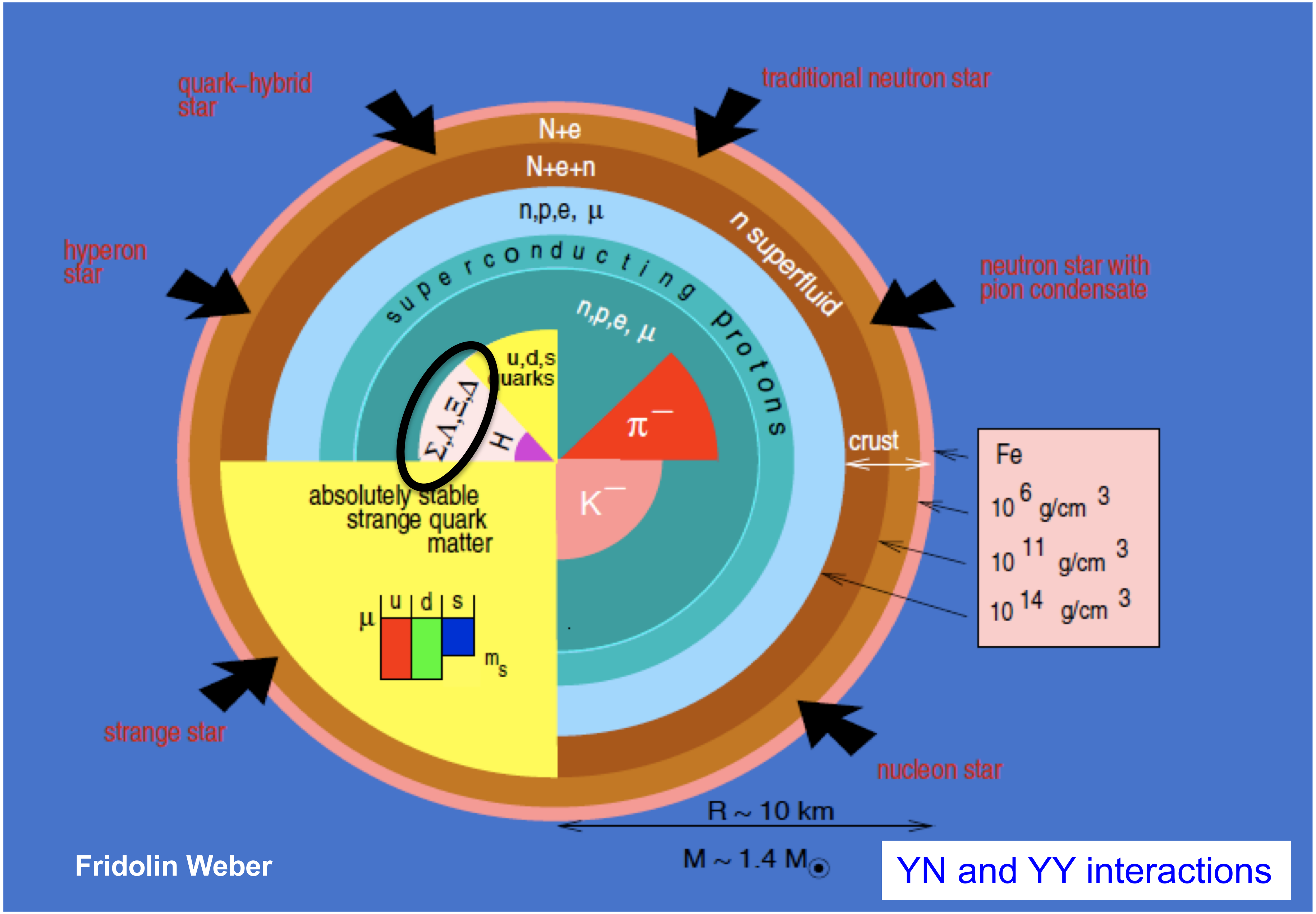


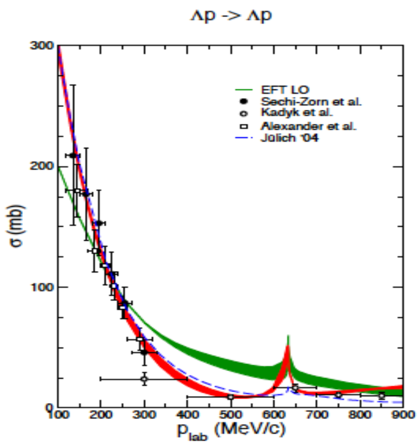
Physics aspects

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

credit: Perez-Obiol

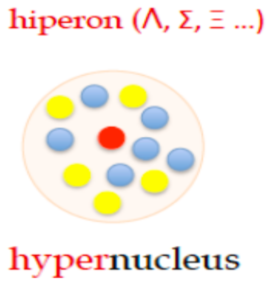
In Neutron Stars





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 ($\Lambda\Lambda$ 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

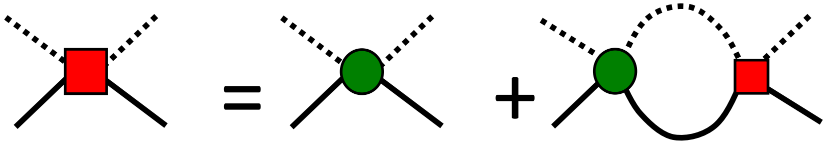
Schaefer, Wagner, Wambach, Kuo and Brown ‘06

- Lattice calculations (HALQCD/NPLQCD)

To solve YN and YY interactions on the lattice

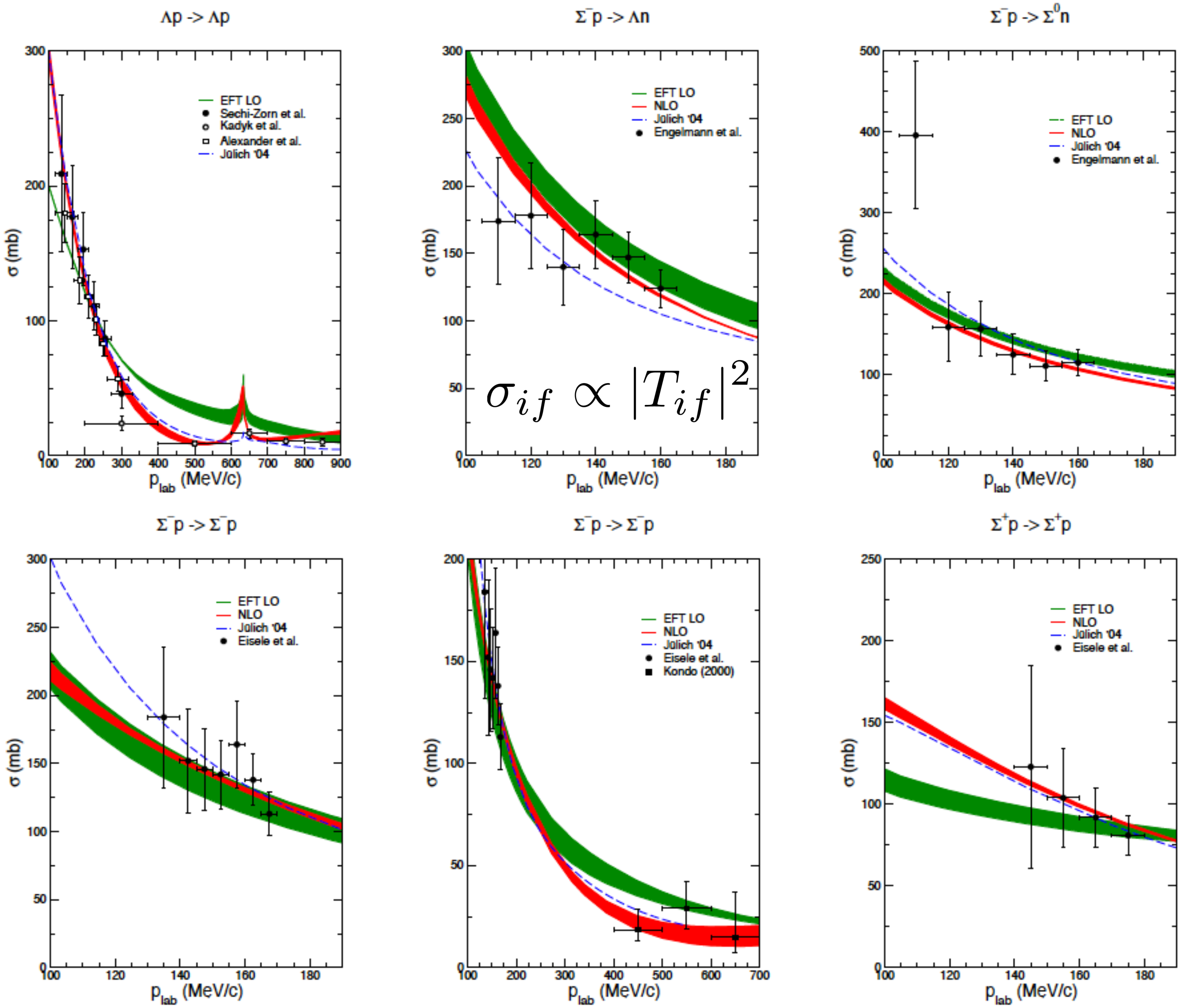
HALQCD: Ishii, Aoki, Hatsuda ‘07; Aoki, Hatsuda and Ishii ‘10; Aoki et al ‘12
NPLQCD: Beane, Orginos and Savage ‘11; Beane et al ’12

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

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

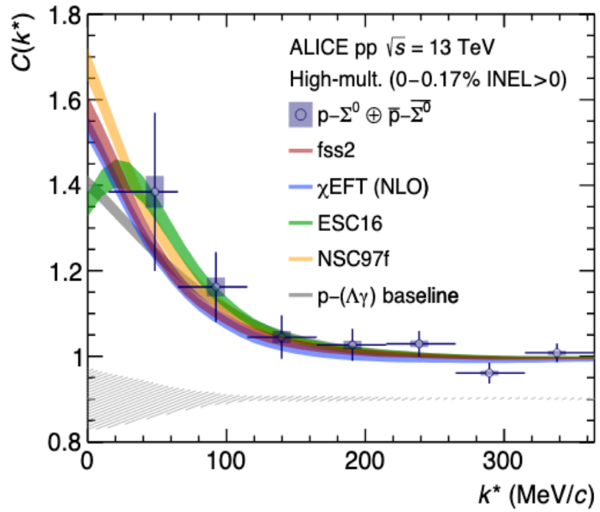


$$\sigma_{if} \propto |T_{if}|^2$$

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

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

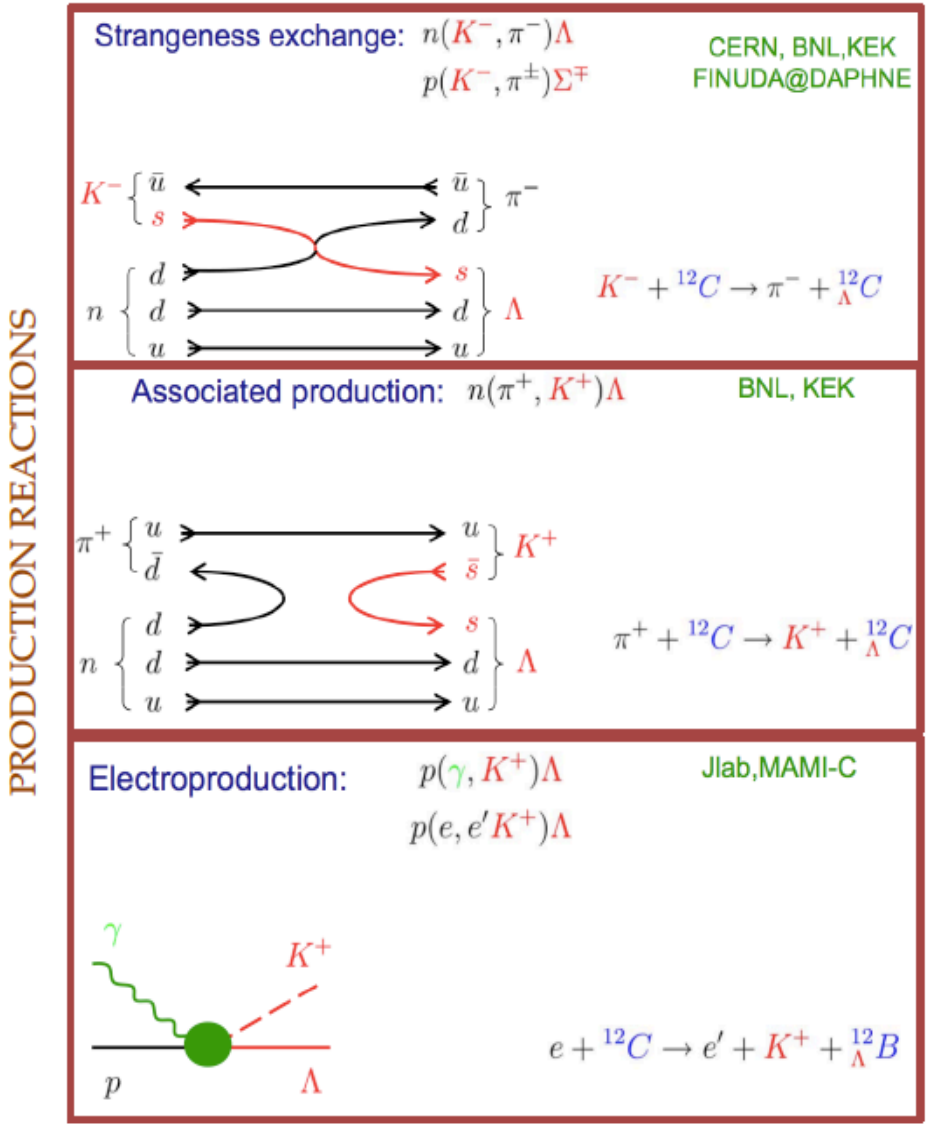
$$k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$$



S. Acharya et al. '19

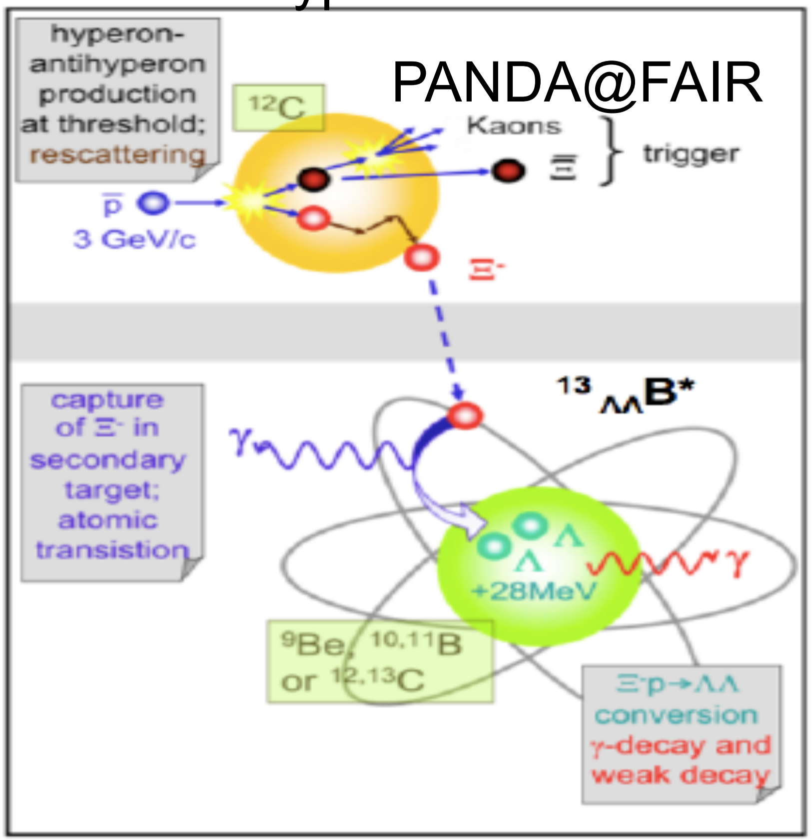
Hypernuclei

Λ hypernuclei



credit: Parreno

Double Λ hypernuclei



credit: Sanchez-Lorente

Also Ξ hypernuclei @ BNL, KEK

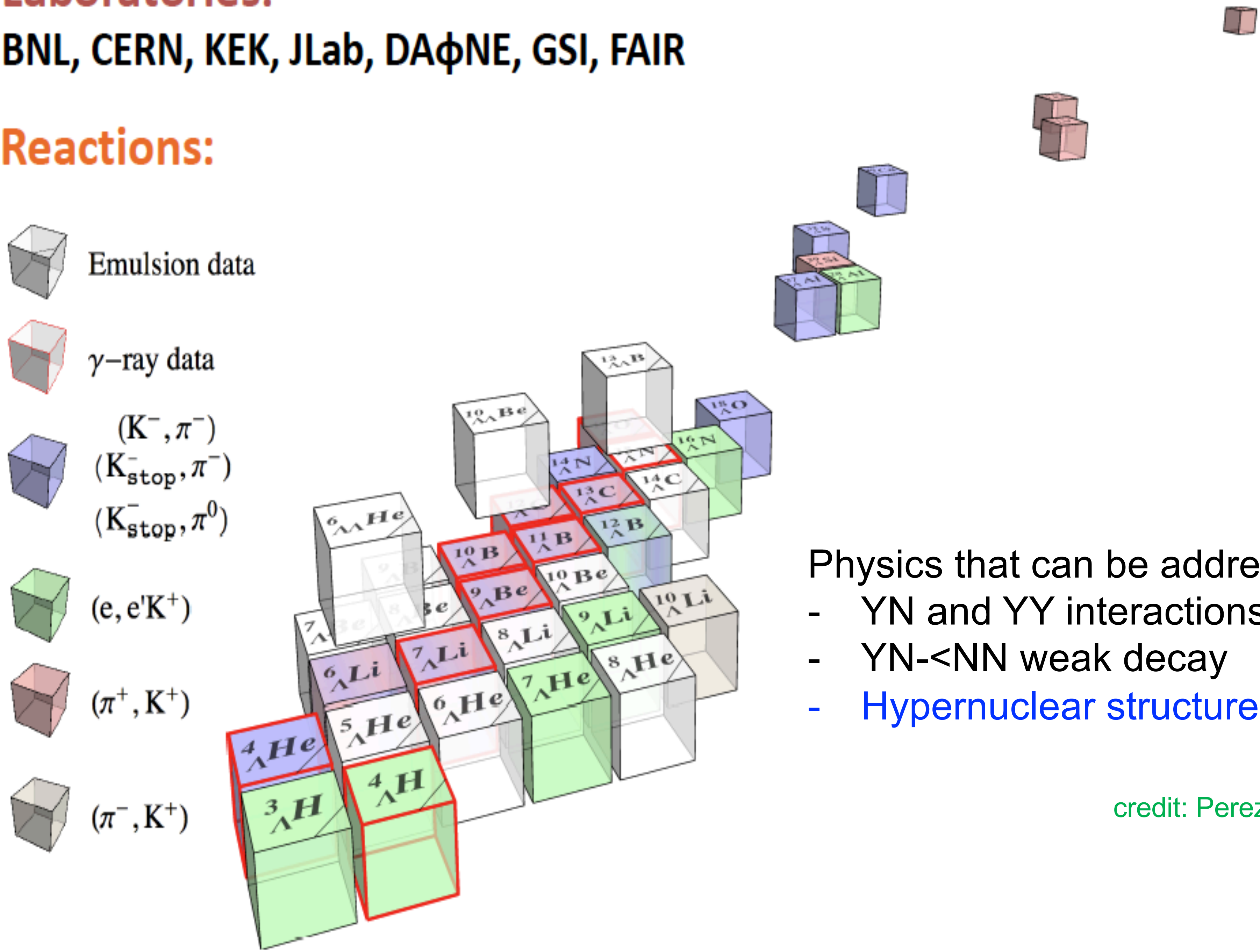
$$^{12}C(K^-,K^+)^{12}_{\Xi^-}Be$$

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

Laboratories:

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

Reactions:

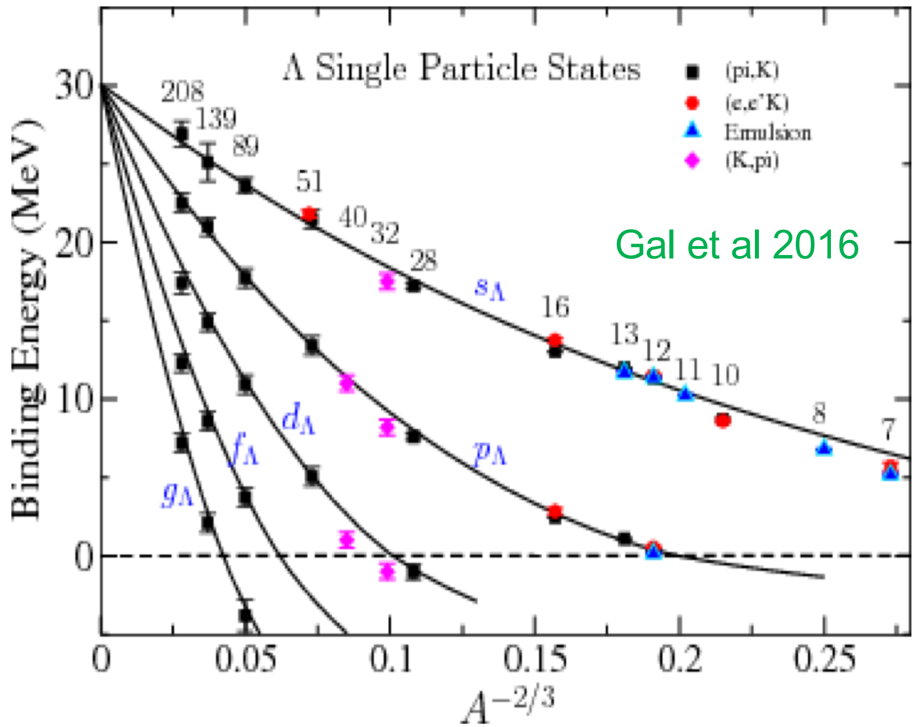


Physics that can be addressed:

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

credit: Perez-Obiol

Binding energy of Λ hypernuclei

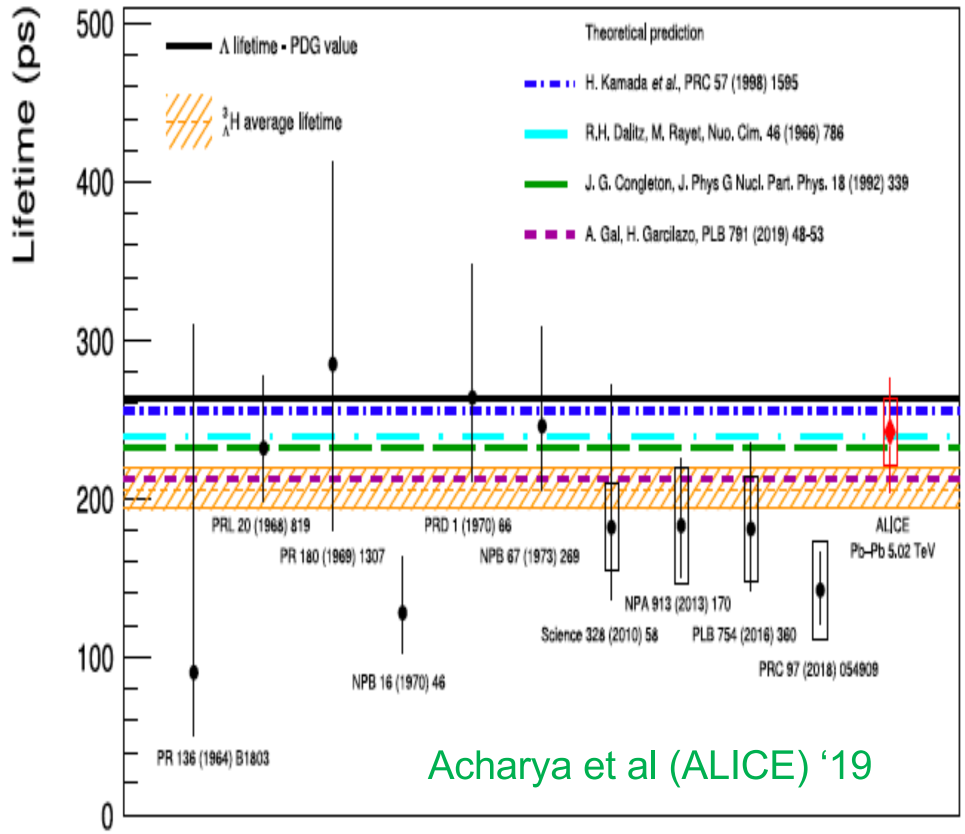


Binding energy of different hypernuclei as function of the mass number

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



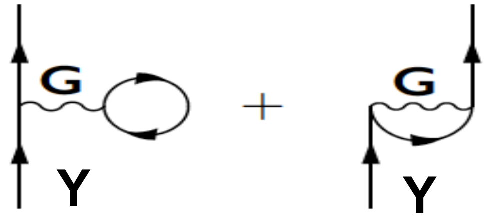
Expected $\tau({}^3_\Lambda H) = \tau(\Lambda)$

$\Leftrightarrow$ 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



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

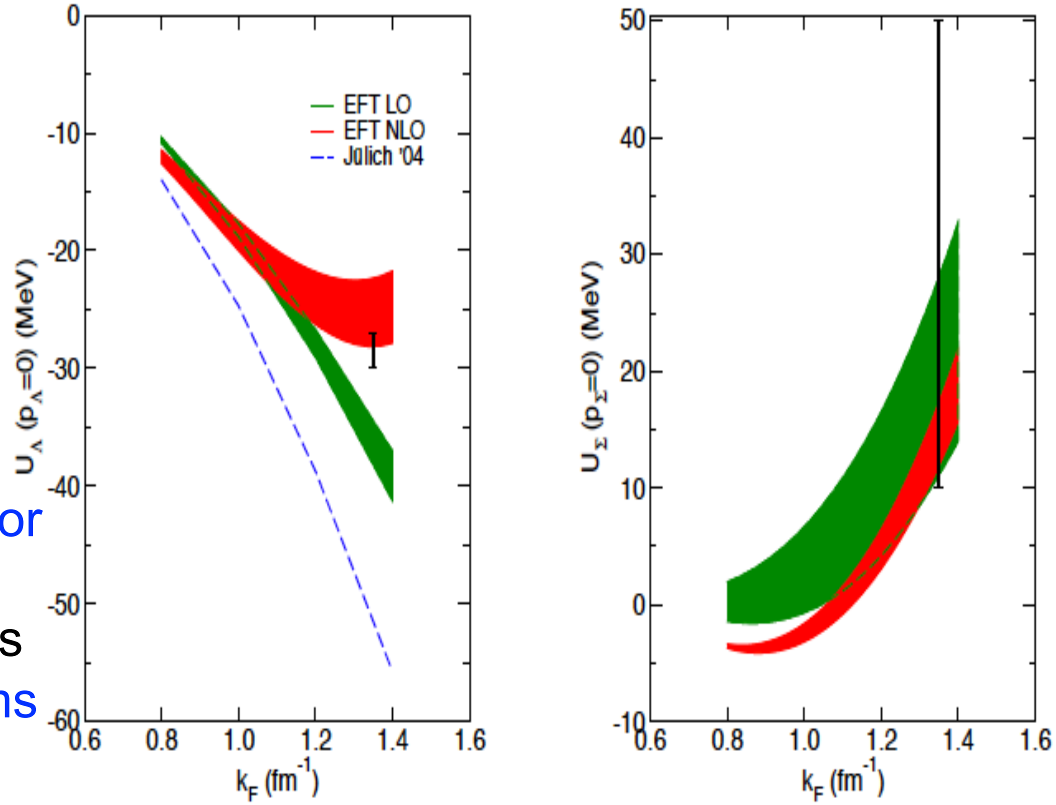
$k_F = 1.35\ \text{fm}^{-1}$ ($\rho_0 = 0.166\ \text{fm}^{-3}$)

	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

* Nemura et al'18

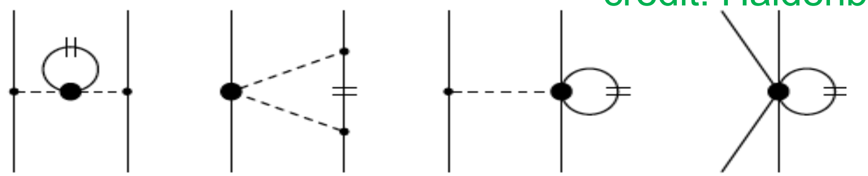


Haidenbauer and Meißner'15

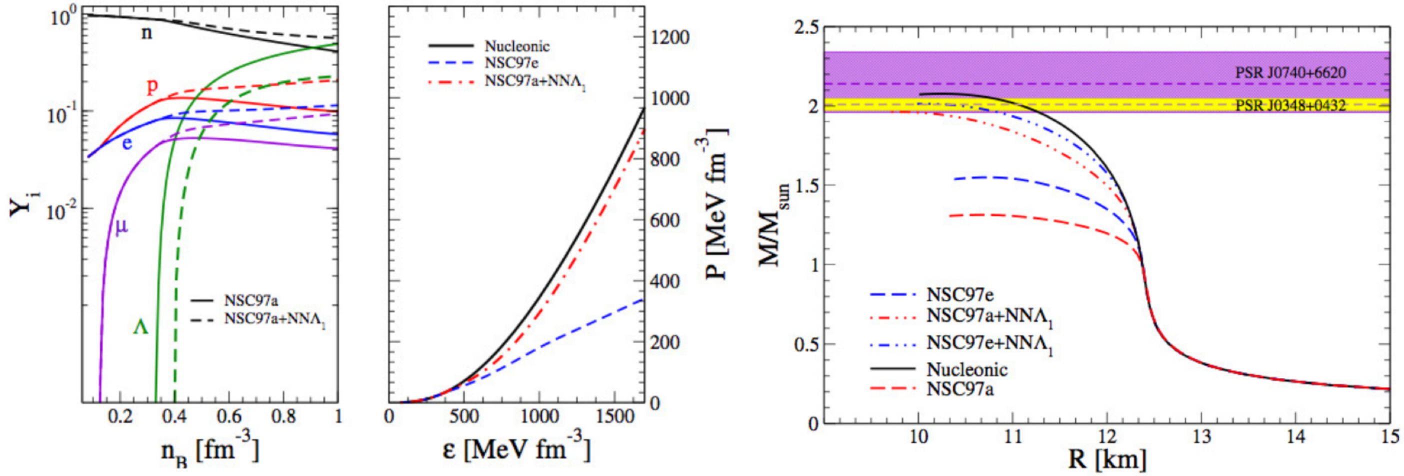
Λ in dense matter: including three-body forces

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?

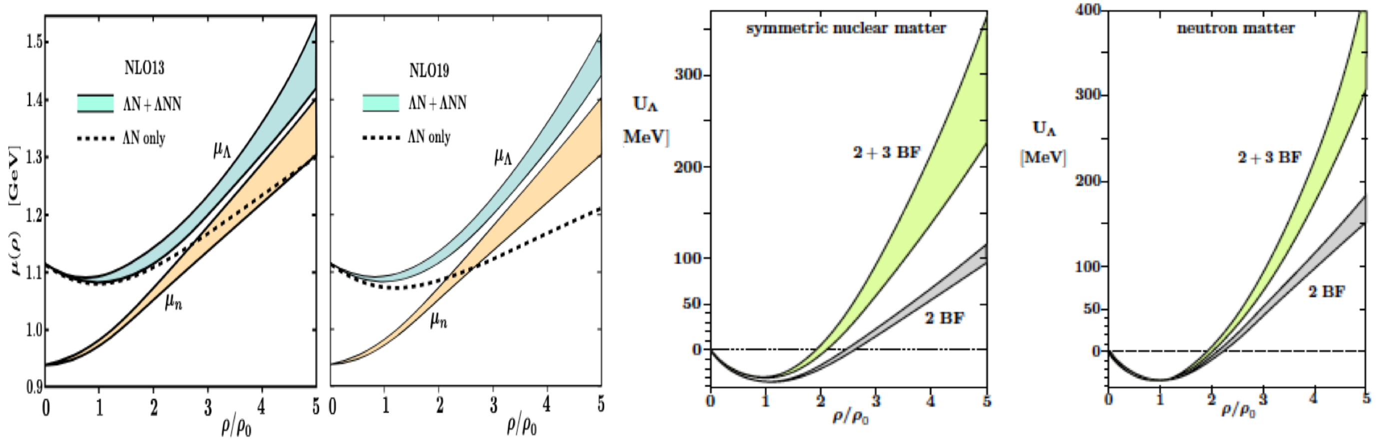


Logoteta, Vidana and Bombaci '19

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



Gerstung, Kaiser and Weise '20

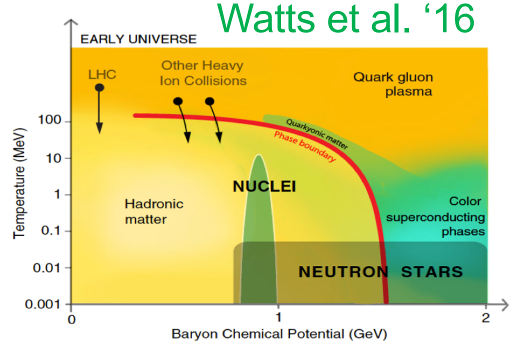
Only symmetric and neutron matter

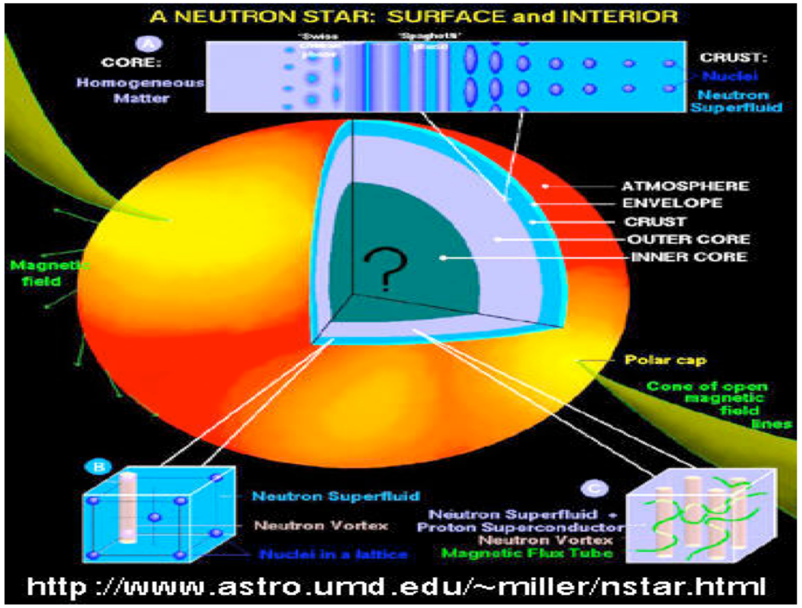
χEFT NN, NNN,NY, NNY

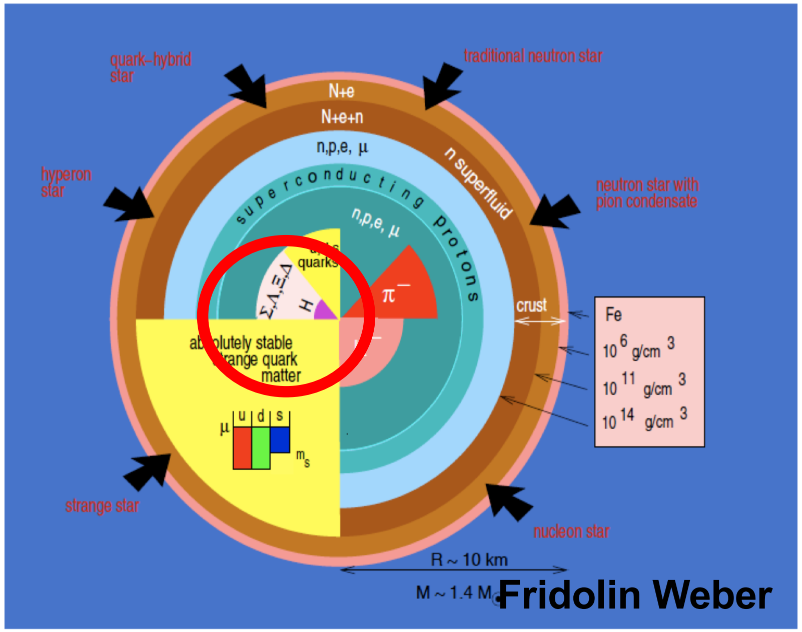
Λ in NS energetically unfavorable, but only neutrons and Λ are considered

Hyperons and Neutron Stars

Watts et al. '16



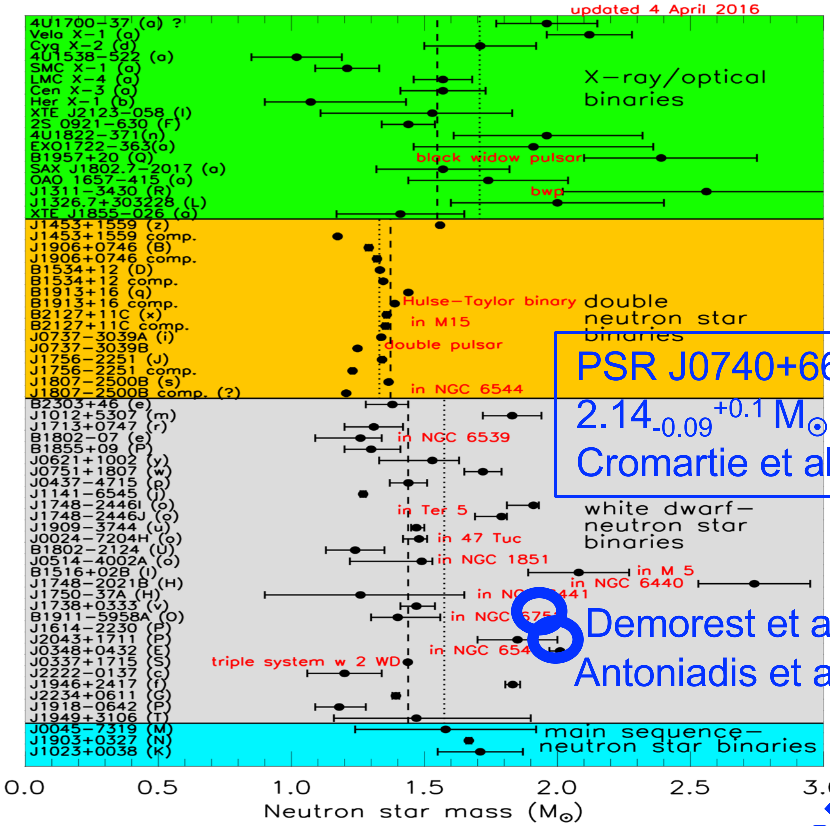




- produced in core collapse supernova explosions, usually observed as pulsars
- usually refer to compact objects with $M \approx 1\text{-}2\ M_\odot$ and $R \approx 10\text{-}12$ Km
- extreme densities up to 5-10 ρ_0 ($n_0 = 0.16\ \mathrm{fm}^{-3} \Rightarrow \rho_0 = 3 \cdot 10^{14}\ \mathrm{g/cm}^3$)
- magnetic field : $B \sim 10^{8..16}$ G
- temperature: $T \sim 10^{6\ldots11}$ K
- observations: masses, radii, gravitational waves, cooling…

Masses

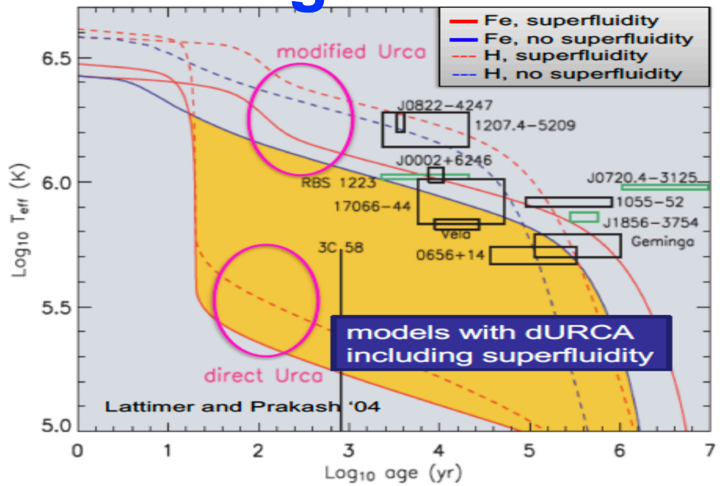
Lattimer '16



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

& Demorest et al '10
Antoniadis et al '13

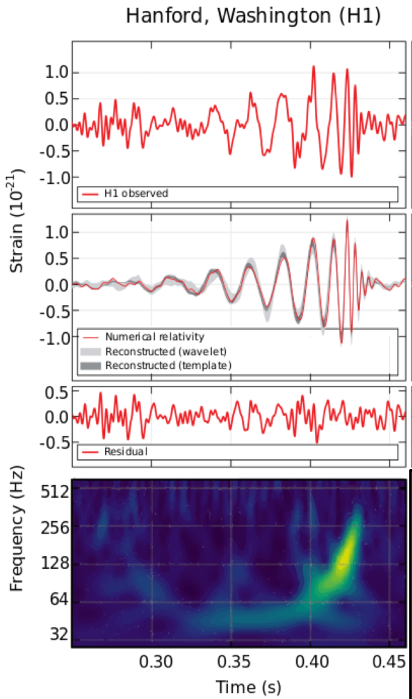
Cooling

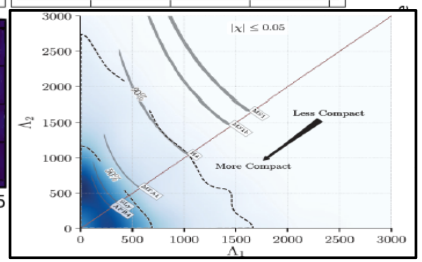


Observations

GW170817

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





..also GW190425, GW190814

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

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

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

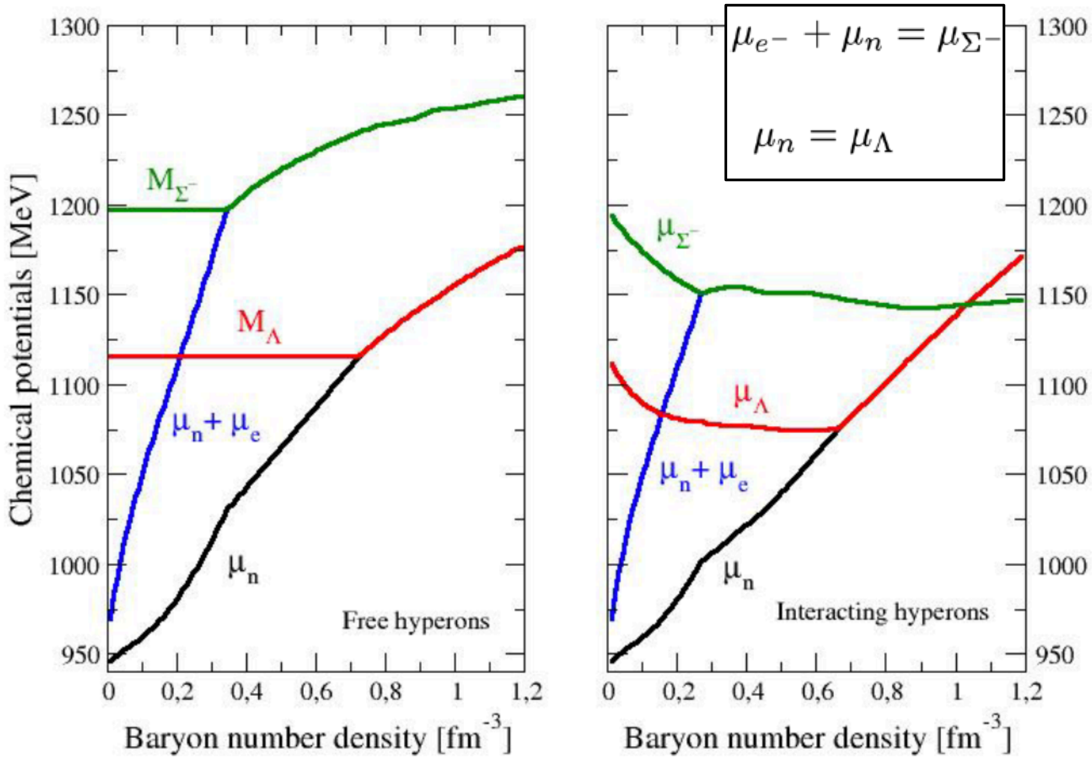
Hyperons might be present at $n \sim (2\text{-}3) n_0$!!!

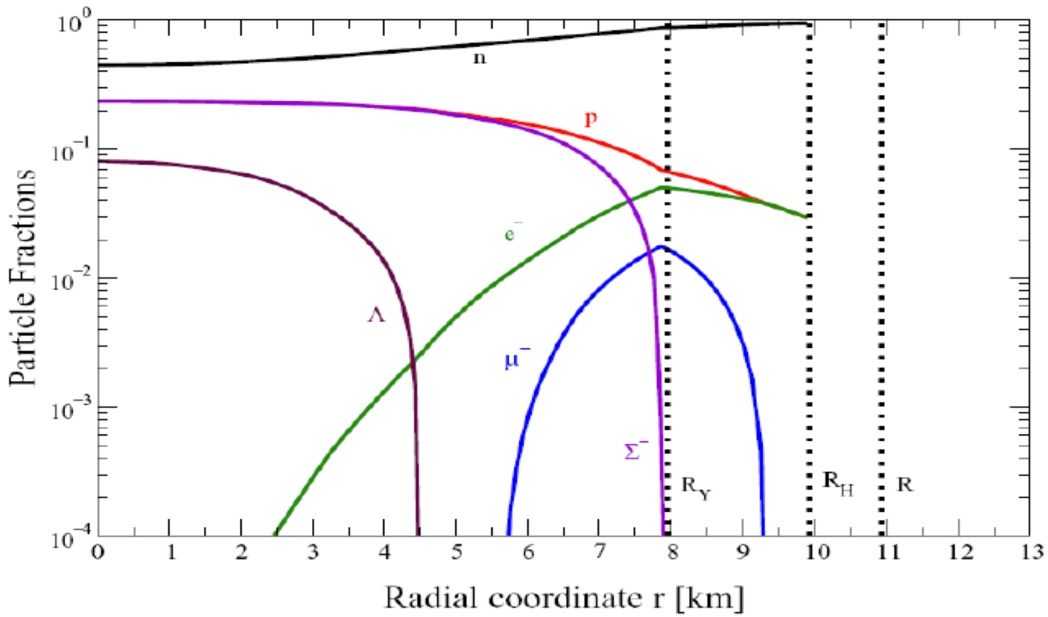
β-stable hyperonic matter

μ_N is large enough to make N->Y favorable

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

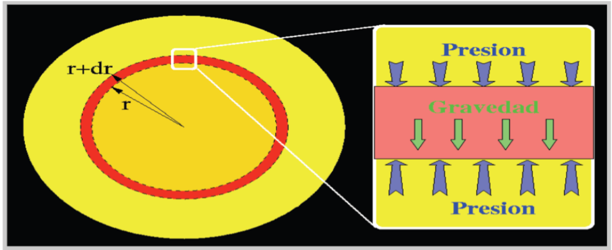
$$\mu_i = b_i \mu_n - q_i \mu_e$$
$$\sum_i x_i q_i = 0$$



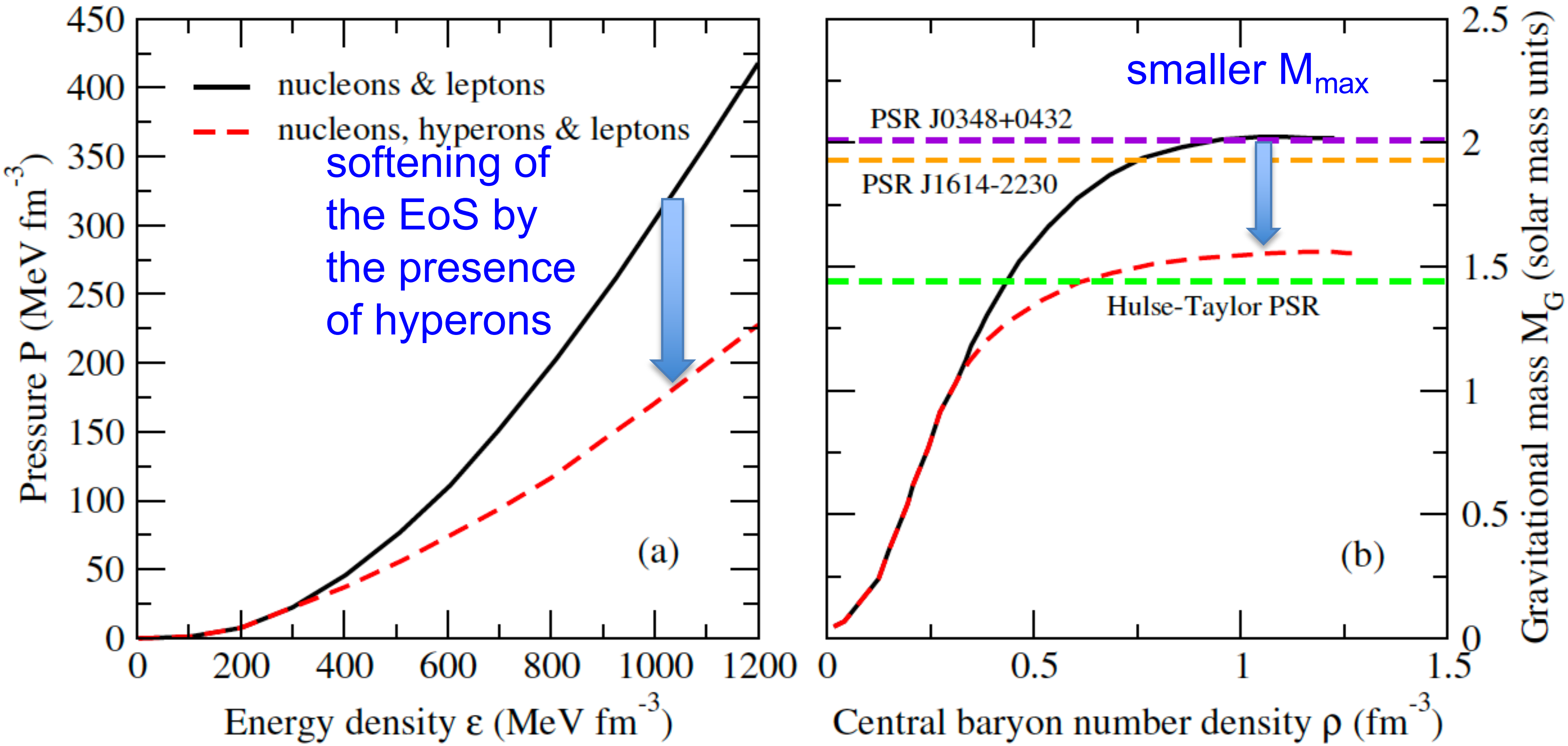


credit: Vidana

Inclusion of hyperons….



credit: 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

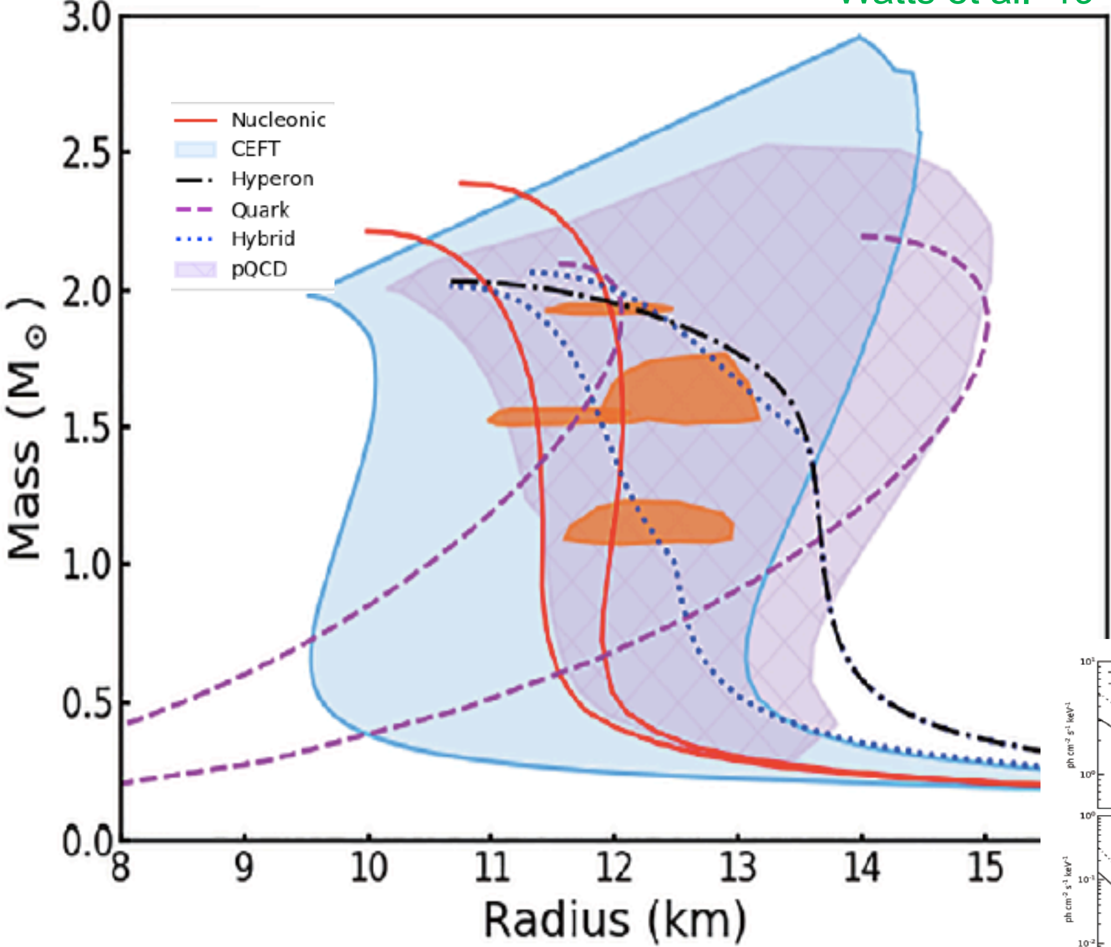
The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to **maximum neutron star masses < $2M_{\odot}$**

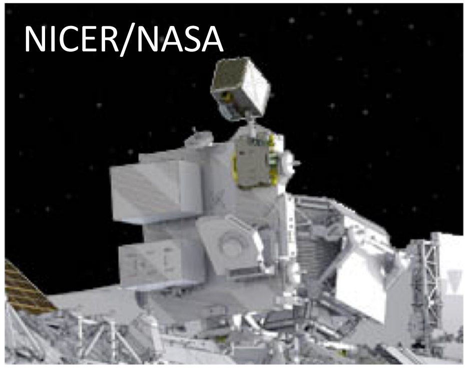
Solution?

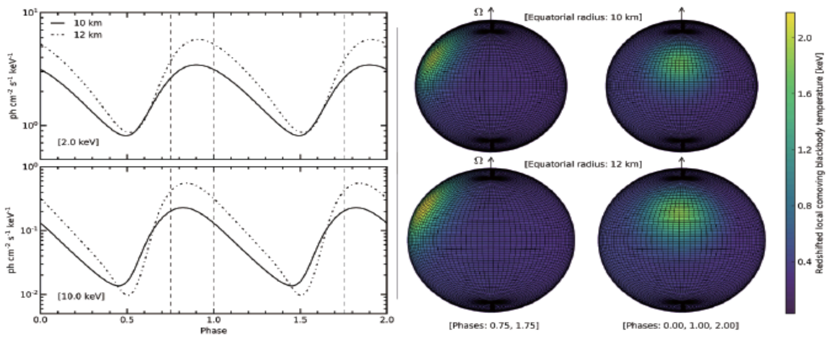
- stiffer YN and YY interactions
- hyperonic 3-body forces
- push of Y onset by Δ-isobars or meson condensates
- quark matter below Y onset
- dark matter, modified gravity theories…

Space missions to study the interior of NS

Watts et al. '19

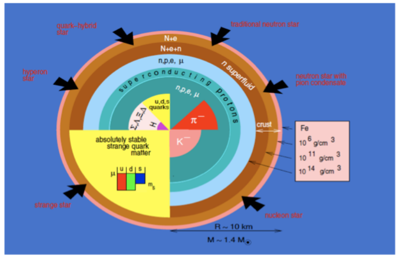




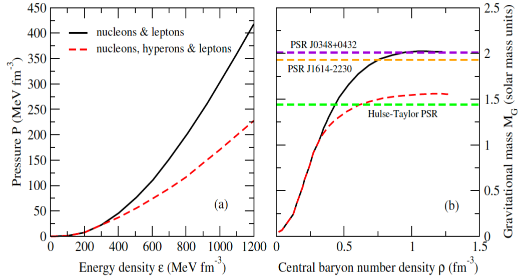


Constraints from pulse profile modelling of rotation-powered pulsars with eXTP

and multimessenger astronomy!



Present and Future



A lot of experimental, observational and theoretical effort has been invested to study 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

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 < $2M_{\odot}$

This is known as **The Hyperon Puzzle**

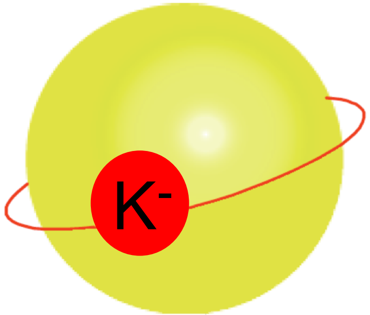
The future of hyperon physics relies on particle and nuclear experiments as well as X-ray and multimessenger astronomy

STRONG 2020

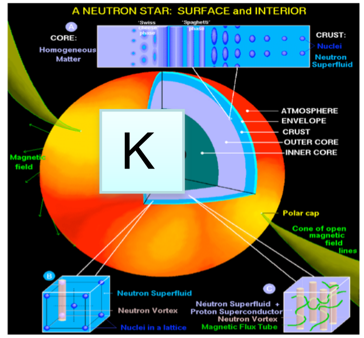
PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN



Strange Mesons

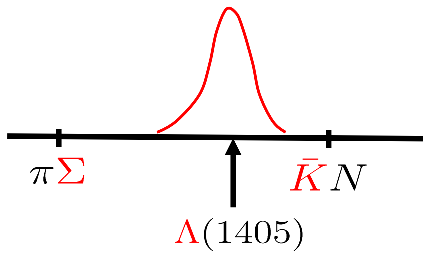


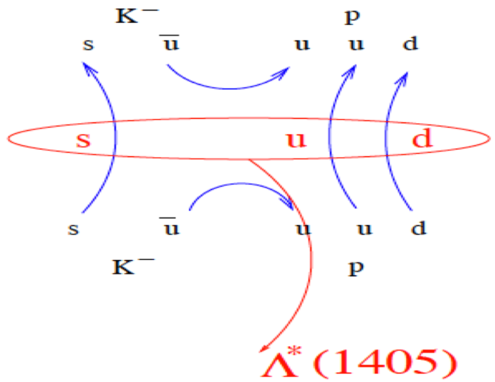
- $\bar{K}N$ interaction: $\Lambda(1405)$ resonance
- $\bar{K}NN$ bound state
- Kaons and Antikaons in matter
- Experiments and observations: from atoms to stars
- Present and Future

$\bar{K}N$ interaction: the Λ(1405)

$$\bar{K} = \begin{pmatrix} \bar{K}^0 \\ -K^- \end{pmatrix} \begin{matrix} \bar{d}\,s \\ \bar{u}\,s \end{matrix} \quad s=-1$$

• $\bar{K}N$ scattering in the I=0 channel is governed by the presence of the Λ(1405) resonance, located only 27 MeV below the $\bar{K}N$ threshold





• 50's: idea originally proposed by Dalitz and Tuan

• since 90's: the study of $\bar{K}N$ scattering has been revisited by means of unitarized theories using meson-exchange models or chiral Lagrangians

meson-exchange models

Mueller-Groeling, Holinde and Speth '90;
Buettgen, Holinde, Mueller-Groeling, Speth and Wyborny '90;
Hoffmann, Durso, Holinde, Pearce and Speth '95;
Haidenbauer, Krein, Meissner and Tolos '11..

chiral Lagrangian

Kaiser, Siegl and Weise, '95; Oset and Ramos '98;
Oller and Meissner '01; Lutz, and Kolomeitsev '02;
Garcia-Recio et al. '03; Jido et al. '03; Borasoy, Nissler, and Weise '05;
Oller, Prades, and Verbeni '05; Oller '06;
Borasoy, Nissler and Weise '05;
Khemchandani, Martinez-Torres, Nagahiro and Hosaka '12
Feijoo, Magas and Ramos '19; Feijoo, Gazda, Magas and Ramos '21;
Ren, Epelbaum, Gegelia and Meissner '20 '21; Bruns and Cieply '22..

more channels,
next-to-leading order,
Born terms beyond WT
(s-channel, u-channel),
fits including new data,
higher partial waves...

Double-pole structure of Λ(1405)

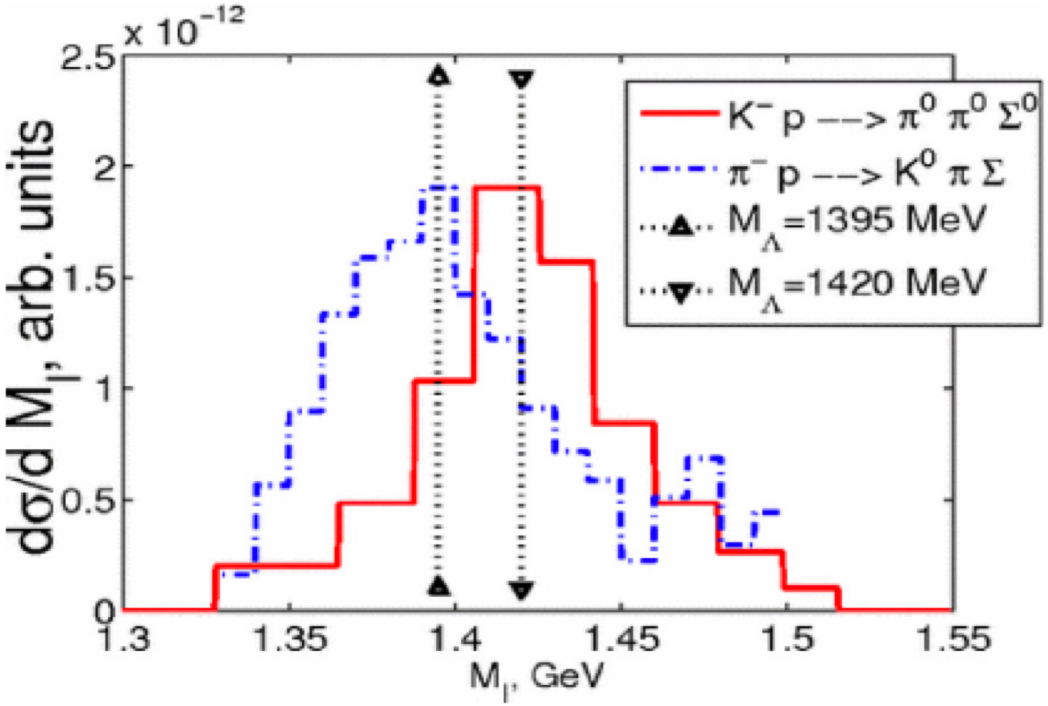
Λ(1405) results from the superposition of two poles in the complex plane, with different coupling to πΣ and $\bar{K}N$ states

$$T_{ij} \approx \frac{g_i g_j}{z - z_R}$$

Pole positions for the $\Lambda(1405)$ coming from recent chiral effective models including the SIDDHARTA constraint.

PDG

Model		First Pole [MeV]	Second Pole [MeV]
NLO	Ikeda, Hyodo and Weise '12	$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
Fit II	Guo and Oller '13	$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
Solution Nr. 2	Mai and Meissner '15	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
Solution Nr. 4	Mai and Meissner '15	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

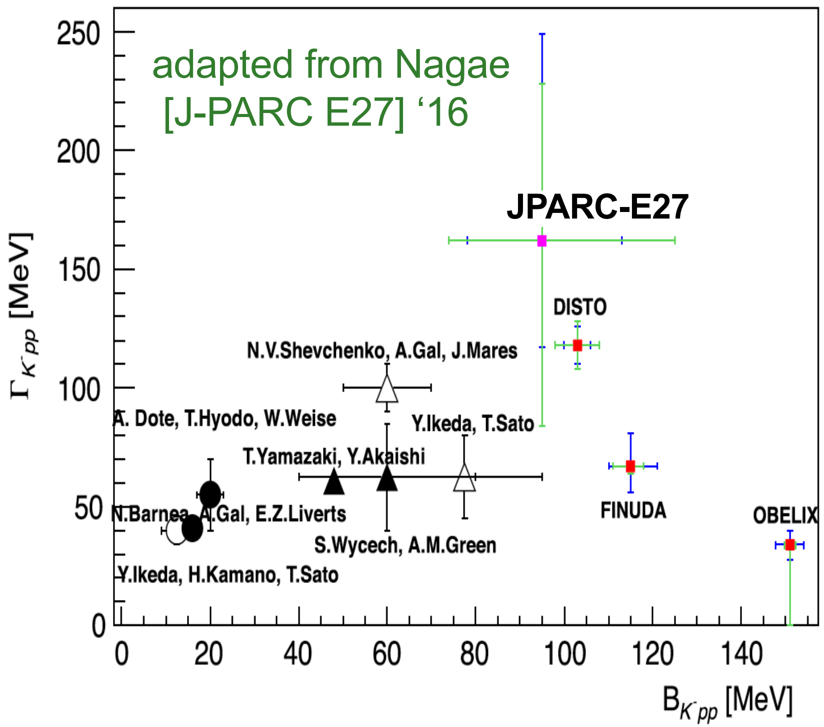


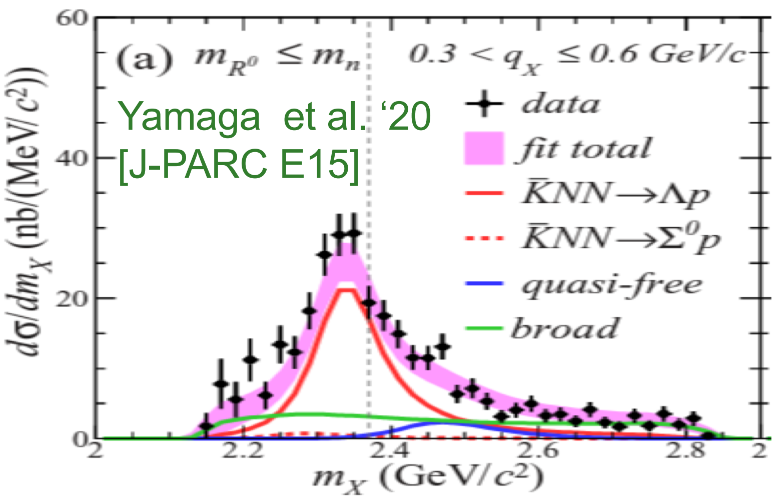
the measured spectra of the Σπ final states associated to the Λ(1405) for kaon- and pion-induced reactions supports the double-pole structure of the Λ(1405)

Magas, Oset and Ramos '05

$\bar{K}NN$ bound state

if the $\bar{K}N$ interaction is so attractive,
the $\bar{K}$-nuclear clusters may form ➔ The $\bar{K}NN$ (I=1/2) state





thoroughly addressed theoretically
Akaishi, Yamazaki, Shevchenko, Gal, Mares, Revai, Ikeda, Sato, Kamano, Dote, Hyodo, Weise, Wycech, Green, Bayar, Oset, Ramos, Yamagata-Sekihara, Barnea, Liverts, Dote, Inoue, Myo, Uchino, Hyodo, Oka..

initial claims by FINUDA, DISTO and OBELIX
that could find a conventional explanation Ramos et al '08 or not be reproduced Agakishiev et al [HADES] '15

more recent experiments did not find any
Tokiyasu et al. [Spring8/LEPS] '14; Hashimoto et al [JPARC E15] '15; Vazquez-Doce et al. [AMADEUS] '16
or if found Ichikawa et al [J-PARC E27] '15; Nagae et al [J-PARC E27] '16
may have other interpretation Garcilazo et al '13

J-PARC E15 found a structure near $\bar{K}NN$ threshold Sada et al [J-PARC E15] '16 being interpreted as $\bar{K}NN$ bound state Sekihara et al '16
More recent J-PARC E15 measurements
Ajimura et al '19; Yamaga et al '20

Binding energy and width of $K^{-}pp$ for different chiral and phenomenological calculations using variational, Faddeev or ccCSM+Feshbach methods.

Tolos and Fabbietti ‘20

Work	B [MeV]	Γ [MeV]	Method	Type of potential
Barnea et al.	16	41	Variational	Chiral
Dote et al.	17–23	40–70	Variational	Chiral
Dote et al.	14–50	16–38	ccCSM	Chiral
Ikeda et al.	9–16	34–46	Faddeev	Chiral
Bayar et al.	15–30	75–80	Faddeev	Chiral
Sekihara et al.	15–20	70–80	Faddeev	Chiral
Yamazaki et al.	48	61	Variational	phenomenological
Shevchenko et al.	50–70	90–110	Faddeev	Phenomenological
Ikeda et al.	60–95	45–80	Faddeev	Phenomenological
Wycech et al.	40–80	40–85	Variational	phenomenological
Dote et al.	51	32	ccCSM	Phenomenological
Revai et al.	32/ 47–54	50–65	Faddeev	Chiral/phenomenological

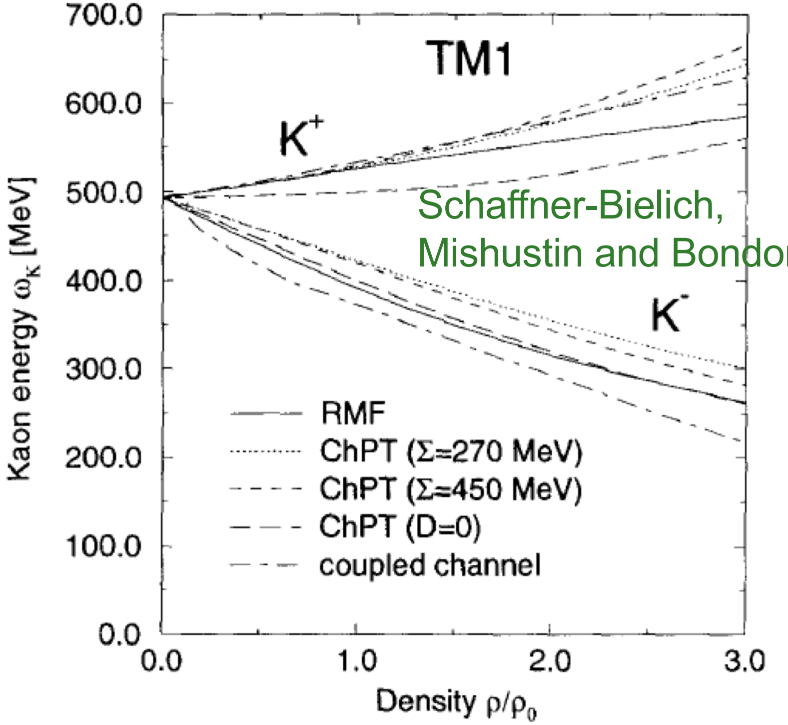
Binding energies **B~9-95 MeV** with decay widths **Γ~16-110 MeV**

Variety of values due to
- uncertainties in subthreshold extrapolation of the $\bar{K}N$ interaction
(chiral interactions give lower binding energies than phenomenological ones)
- use of variational or Faddeev calculations introduces certain approximations
(full three-body not account for in variational methods, whereas Faddeev calculations deal with separable two-body interactions), and ccCSM combines merits of variational and Faddeev but high computational cost

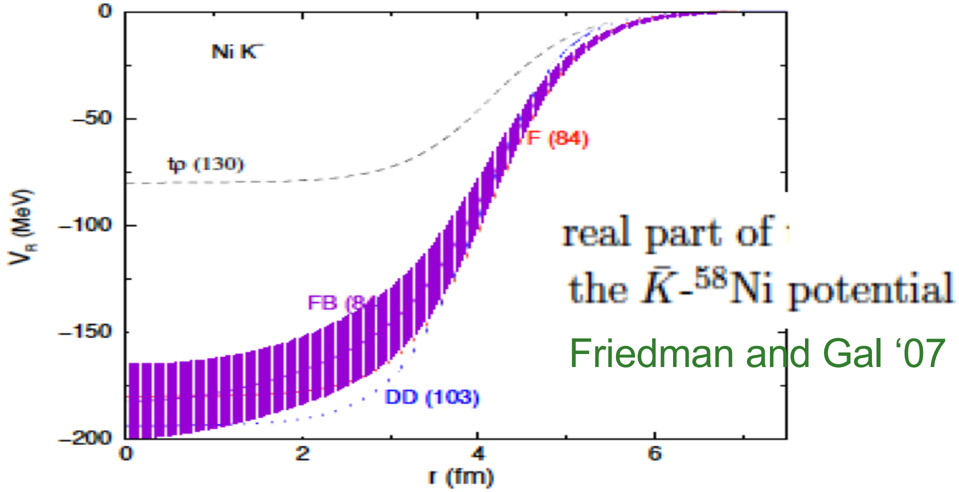
Antikaons in matter

Relativistic mean-field,
Quark meson coupling models…

RMF: early works based on meson-exchange picture or the chiral approach for the $\bar{K}N$ interaction on the mean-field level and fit the parameters to the $\bar{K}N$ scattering length



Phenomenological models
density dependent potentials fitted to kaonic atoms



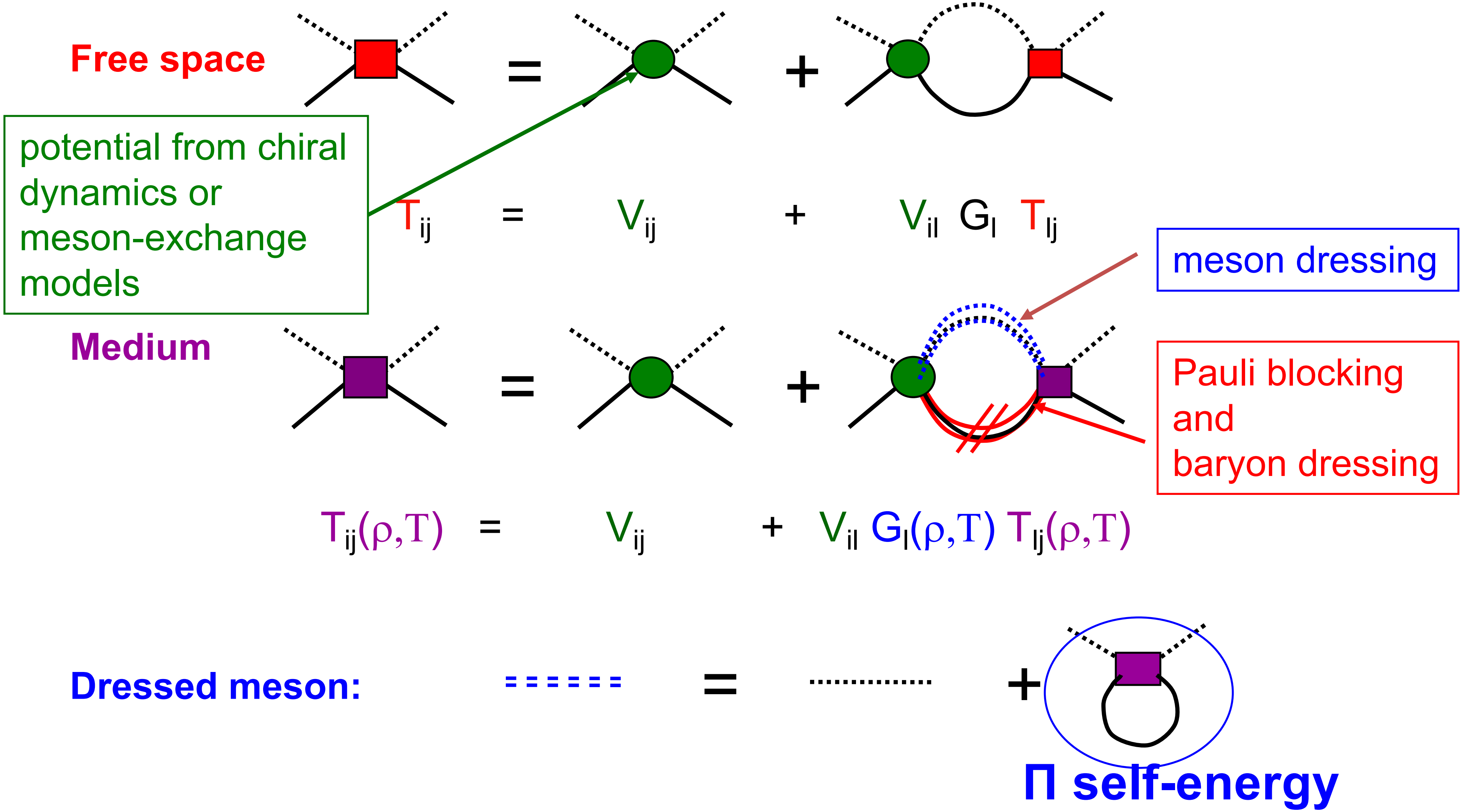
$U_{K-}(\rho_0)$ ~ -100 to -200 MeV

recent K^-N scattering amplitudes from χSU(3) EFT supplemented with phenomenological terms for K^- multinucleon interactions:
kaonic atoms test densities $\rho < \rho_0$

Friedman and Gal '17

Unitarized theory in matter:

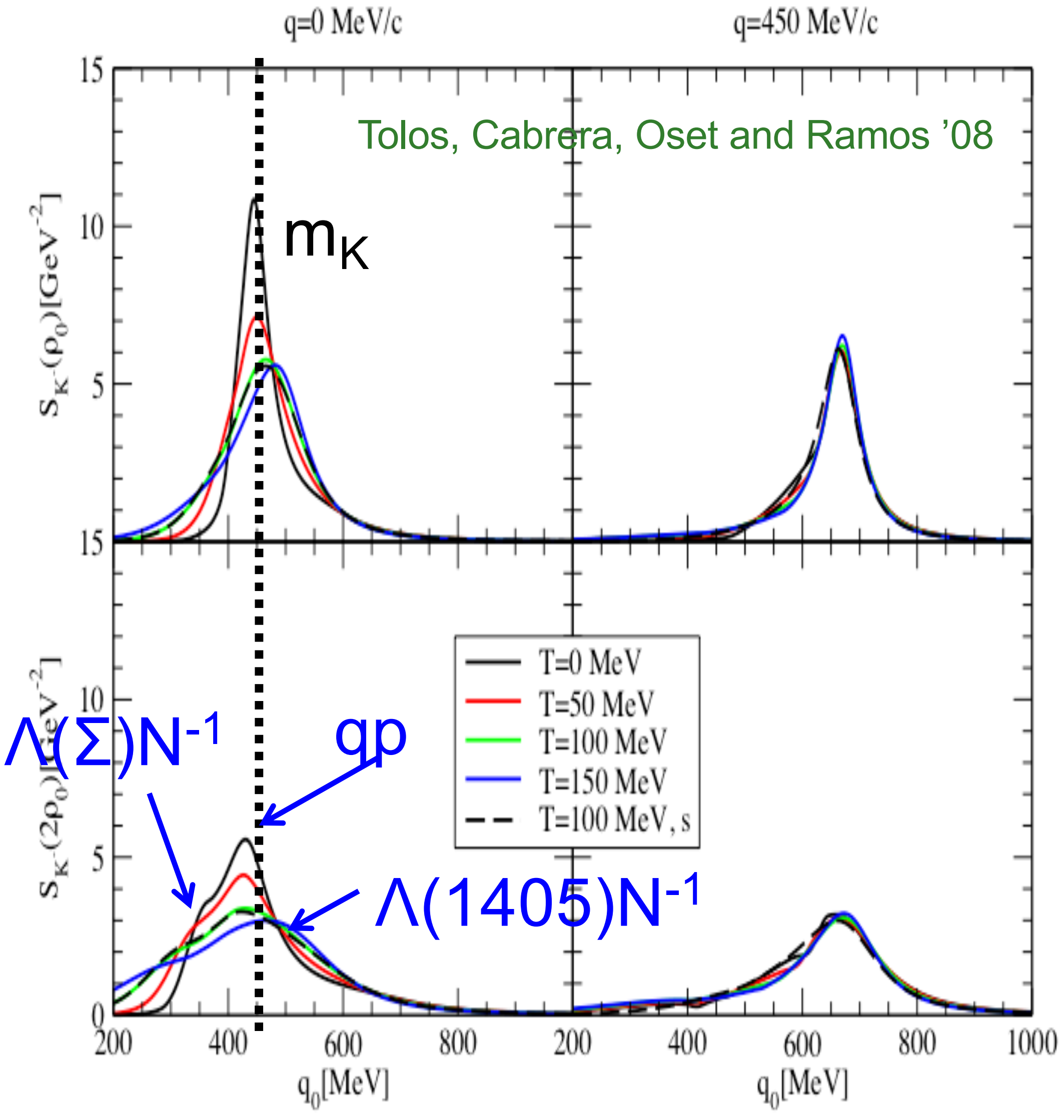
selfconsistent coupled-channel procedure



$\bar{K}$ spectral function in matter

$$S = -\frac{1}{\pi} \frac{\mathrm{Im}\Pi}{[q_0^2 - \vec{q}^{\,2} - m^2 - \mathrm{Re}\Pi]^2 + \mathrm{Im}\Pi^2}$$

Koch ’94; Waas and Weise ’97; Kaiser et al ’97; Oset and Ramos’98; Lutz ’98; Schaffner-Bielich et al ’00; Ramos and Oset ’00; Lutz et al ’02 ; Tolos et al ’01 ’02; Jido et al ‘02 ’03; Magas et al ’05; Tolos et al ’06 ’08; Lutz et al ’08; Cabrera et al ’14…



Re $U_{K^-}(\rho_0)$ ~ -50 to -80 MeV

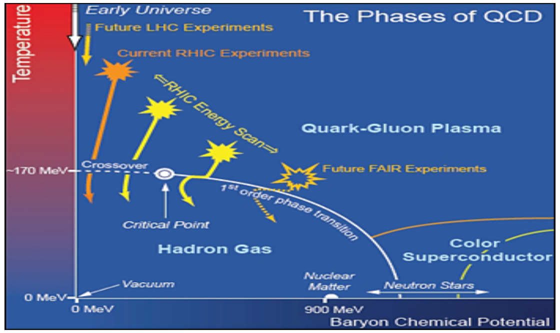
Im $U_{K^-}(\rho_0) \gtrsim$ Re $U_{K^-}(\rho_0)$

- **s-wave** $\bar{K}N$ interaction governed by $\Lambda(1405)$: attraction due to modified $\Lambda(1405)$ in the medium using a self-consistent coupled-channel approach

- **p-wave (and beyond)** contributions to $\bar{K}N$ interaction: not important for atoms but important for heavy-ion collisions due to large momentum

Experiments and observations: from HICs….

credit: DOE



strangeness production in matter
is one of the major research domains in heavy-ion collisions from SIS/GSI to LHC and RHIC up to the future FAIR/NICA/BESII/J-PARC-HI

low-energy HICs:

KaoS/SIS18: K^+,K^- ,..

FOPI/SIS18: K^+,K^-, $\phi(1020)$..

HADES/SIS18: K^+, $K^*(892)^0$, K_s^0, $\phi(1020)$, Λ, $\Xi(1321)$,Ω..

(FOPI) Ritman et al '95; Crochet et al '00; Bastid et al, '07; Zinyuk '14..
(KaoS) Menzel et al '00; Ploskon '05; Uhlig et al '05;Foerster et al '07..
(HADES) Agakishiev et al '09 '10 '11 '13 '14;
Galatyuk '17; Adamczewski-Musch '18 '19...

high-energy HICs:

STAR/RHIC: $K^*(892)^0$, $\phi(1020)$, Ω..

ALICE/LHC: $K^*(892)^0$, $\phi(1020)$, $\Sigma^{+-}(1385)$, $\Xi(1530)^0$..

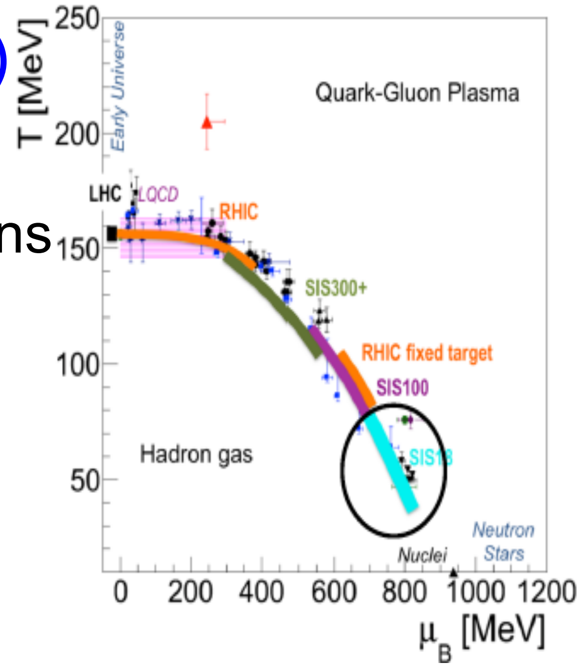
Adams et al. (STAR) '05
Aggarwal et al (STAR) '11
Kumar et al (STAR) '15
Abelev (ALICE) '15
Adam (ALICE) '16
Badala (ALICE) '17..

future:

CBM/FAIR
BM@N/NICA
BESII/RHIC
J-PARC-HI

CBM (FAIR) Physics Book '11
NICA: http://theor0.jinr.ru/twiki-cgi/view/NICA
Aggarwal et al (BES STAR White Paper) '10
JPARC: http://silver.j-parc.jp/sako/white-paper-v1.21.pdf-HI

K^- and K+ at high μ_B (**FOPI/HADES @ SIS18**)



KaoS: from systematics of the experimental results and detailed comparison to transport model calculations
Foerster et al (KaoS) '07

- K^+ probe a soft EoS
- K^+ and K^- yields are coupled by strangeness exchange:

$$NN \rightarrow K^+YN$$
$$K^-N \Leftrightarrow \pi Y$$

- K^+ and K^- exhibit different freeze-out conditions
- repulsion for K+ and attraction for K- seemed to be confirmed

but, for example, what is the role of $\phi \rightarrow K^+ K^-$?

Results from **HADES** and **FOPI** indicate
Zinyuk et al (FOPI)'14; Gasik et al (FOPI) '16; Piasecki et al (FOPI) '16; Adamczewski-Musch et al (HADES) '17..

- K^+ in-medium potential is repulsive: $U_{KN}(\rho_0) \approx 20...40$ MeV
- K^- from Φ decay wash out the effects of the potential (spectra and flow!!)
- separate direct kaons (→ COSY)/elementary reactions
- more systematic, high statistic data on K^- production necessary

conclusions from Leifels-SQM2017

Recent results on kaon and antikaon production in HiCs using a PHSD model with in-medium strange mesons compared to KaoS, FOPI and HADES experimental data

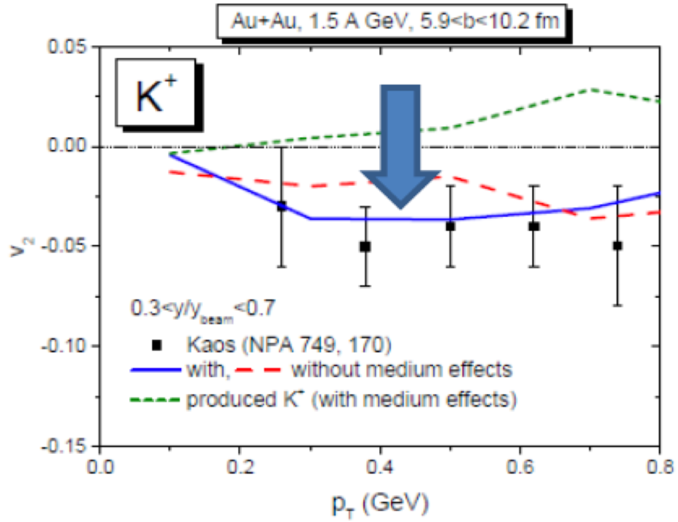
- The nuclear effects on (anti)kaon are more prominent in the collision of large nuclei

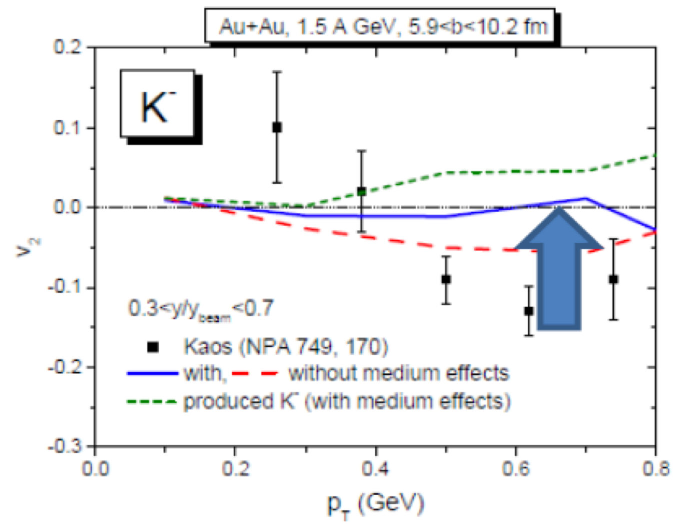
- (Anti)kaon production is (enhanced)suppressed due to (broadening of spectral function)repulsive kaon potential

- (Anti)kaon spectrum becomes (softer)harder in nuclear matter, whereas y-distribution (shrinks)broadens

- Different behaviour of v1/v2 for antikaons and kaons due to the attractive vs repulsive character of the interaction with nucleons

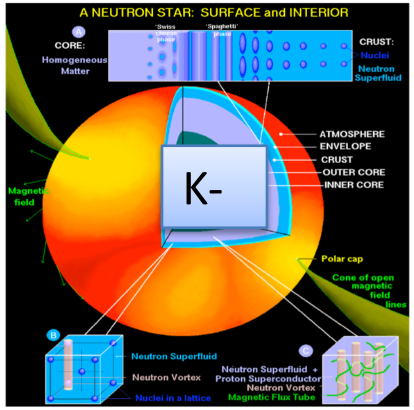
- A moderate EoS (K~300 MeV) reproduces the experimental HiC data better





Song, LT, Wirth, Aichelin and Bratkovskaya '21

Experiments and observations:
…. to stars

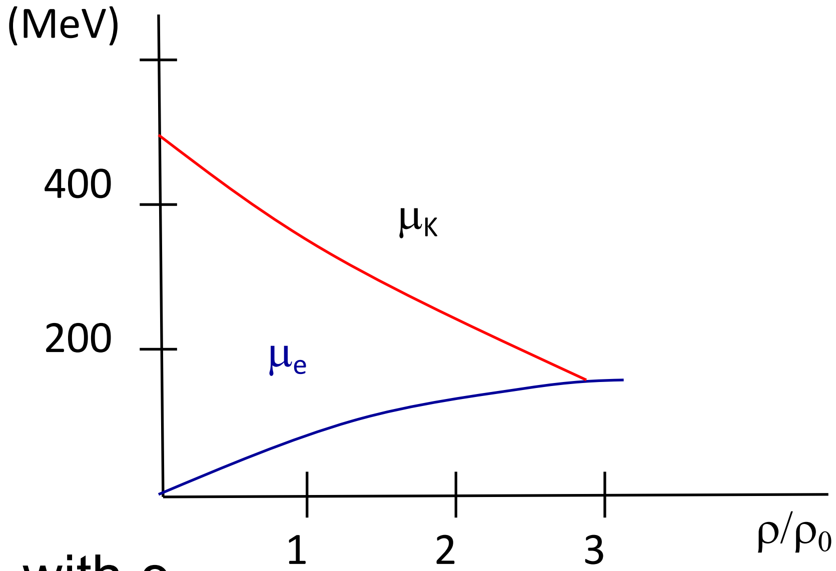


Kaon condensation in neutron stars

K⁻ feels attraction in the medium
→ Kaon condensation in neutron stars?

$$n \leftrightarrow p\, e^- \,\bar{\nu}_e \quad \rightarrow \quad \mu_n = \mu_p + \mu_{e^-}$$

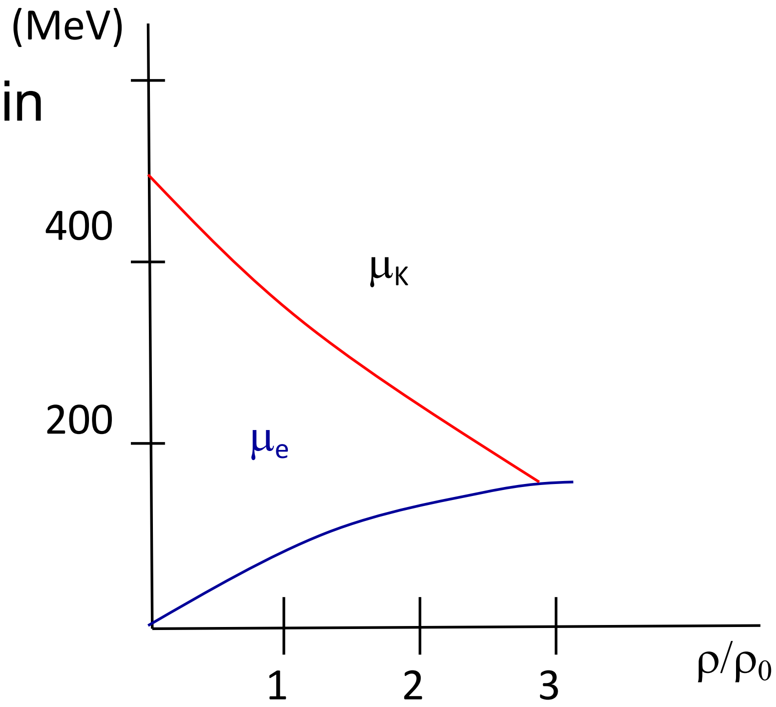
$$n \leftrightarrow p\, K^- \quad \rightarrow \quad \mu_n = \mu_p + \mu_{K^-}$$



Antikaons are bosons. If $\mu_{K^-} \leq \mu_{e^-}$ for $\rho \geq \rho_c$, with ρ_c being a feasible density within neutron stars, antikaons will condensate

Using microscopic unitarized schemes…

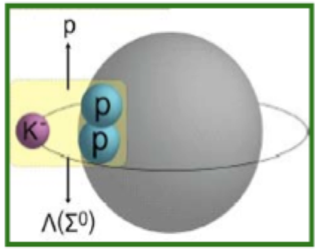
The condition $\mu_{e-} \geq m^*_{K-}$ for a given ρ_c implies that $m_{K-} - m^*_{K-}(\rho_c) \approx 200, 300$ MeV. However, unitarized schemes based on meson-exchange models or chiral Lagrangians predict a moderate attraction in nuclear matter

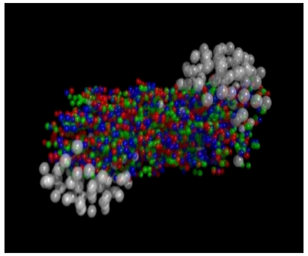


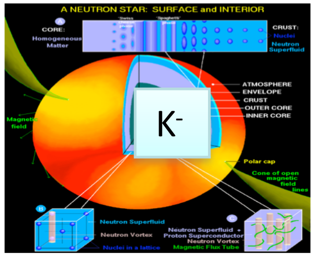
Lutz '98
Ramos and Oset '00
Tolos, Polls, Ramos '01
Tolos, Ramos and Oset '06
Tolos, Cabrera and Ramos '08
Cabrera, Tolos, Aichelin and Bratkovskaya'14

Therefore,
kaon condensation seems very unlikely within microscopic unitarized schemes

Present and Future







A lot of experimental and theoretical effort has been invested to understand the $\bar{K}N$ interaction, that is governed by the presence of the $\Lambda(1405)$

A lot of effort has been invested in unveiling the nature of $\Lambda(1405)$, and the consequences for the formation of $\bar{K}NN$ bound state

Kaons and antikaons in matter have been also investigated in connection to strangeness in nuclear collisions and kaon condensation in neutron stars

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