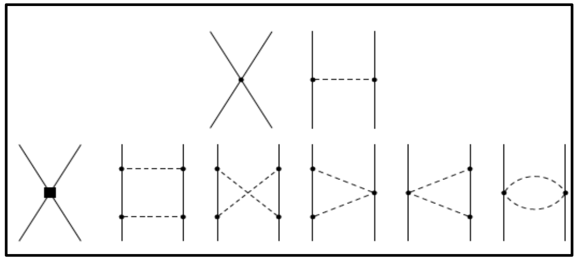

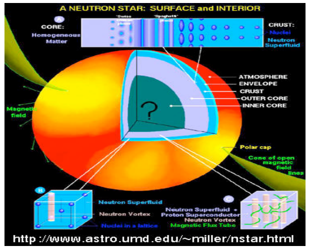

Hyperon interaction with dense nuclear matter and link to neutron stars

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CSIC Consejo Superior de Investigaciones Científicas

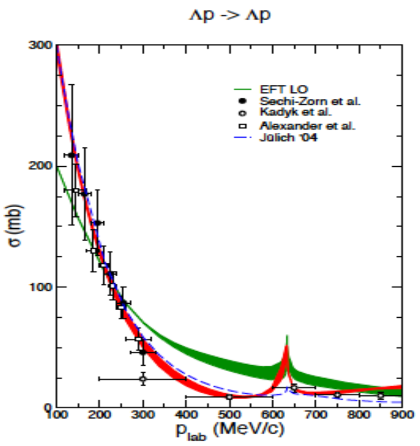
IEEC

STRANGENESS IN QUARK MATTER SQM Bari 2019

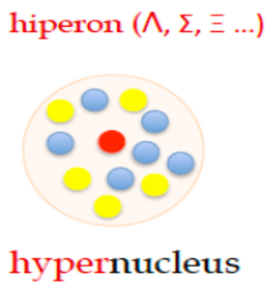
The 18th International Conference on
Strangeness in Quark Matter (SQM 2019)
10-15 June 2019, Bari (Italy)

Outline

- YN and YY interactions
- Theoretical approaches to YN and YY
- YN and YY interactions in χEFT
- Hyperons and Neutron Stars
- Summary



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)
- single Ξ-hypernuclei (ΞN attractive)
- no evidence of Σ-hypernuclei (ΣN repulsive)

Theoretical approaches to YN and YY

- Meson 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

This talk!

- 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)

T. Hatsuda (HALQCD) talk

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

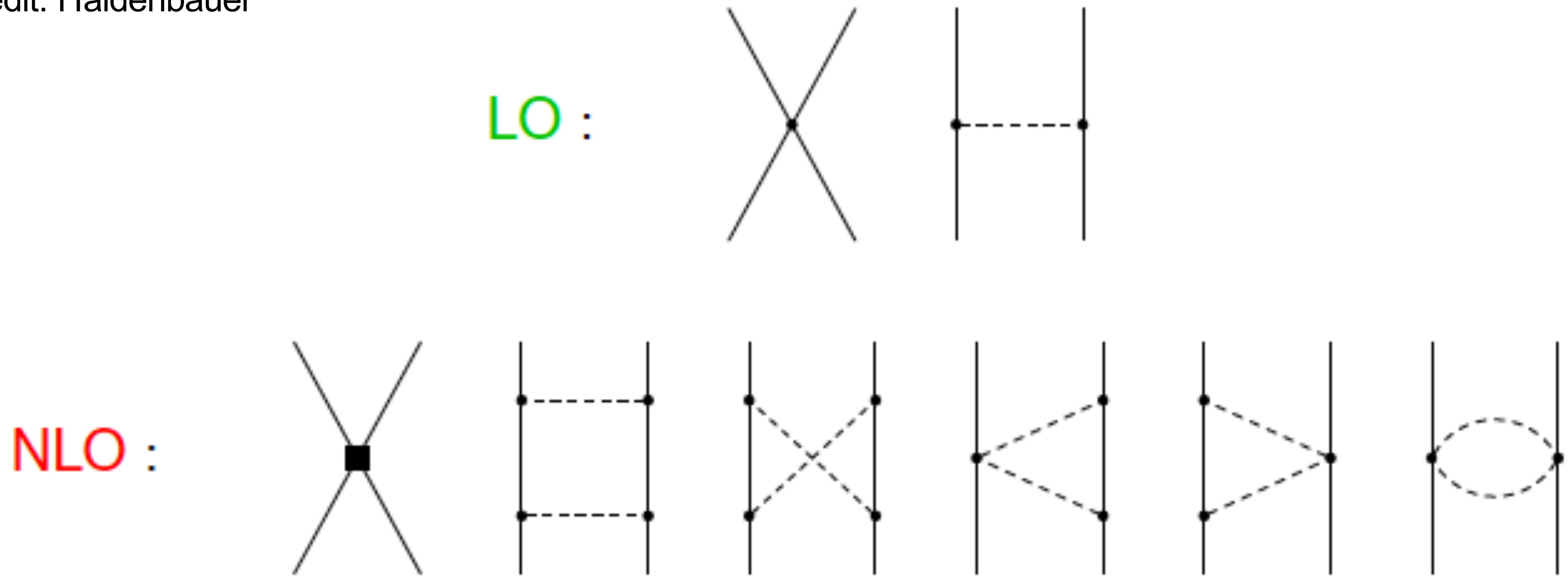
YN and YY interactions in χEFT

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

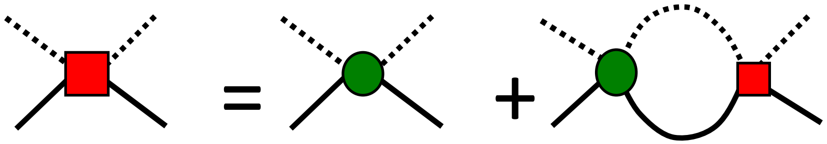
Degrees of freedom: **octet of baryons** (N, Λ ,Σ, Ξ) & **pseudoscalar mesons** (π,K,η)
Diagrams: **pseudoscalar-meson exchanges and contact terms**

credit: Haidenbauer



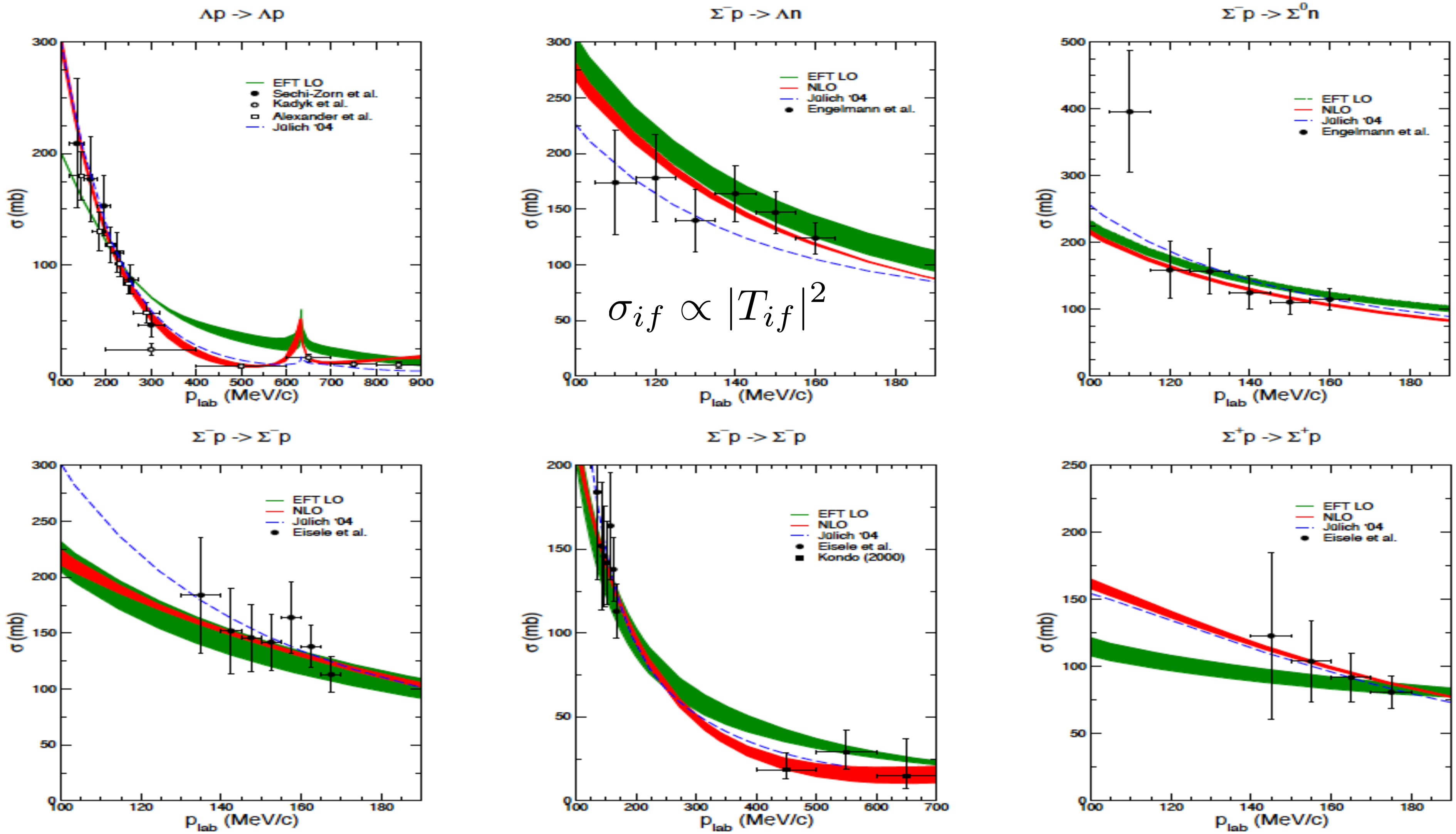
LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.H., N. Kaiser, U.-G. Meißner, A. Nogga, S. Petschauer, W. Weise, NPA 915 (2013) 24

ΛN and ΣN scattering data: the coupled-channel Lippman-Schwinger Equation

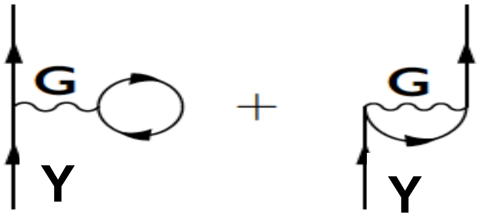


$$T = V + V\frac{1}{E_0 - H_0 + i\eta}T$$

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



Λ and Σ in dense matter: Brueckner-Hartree-Fock



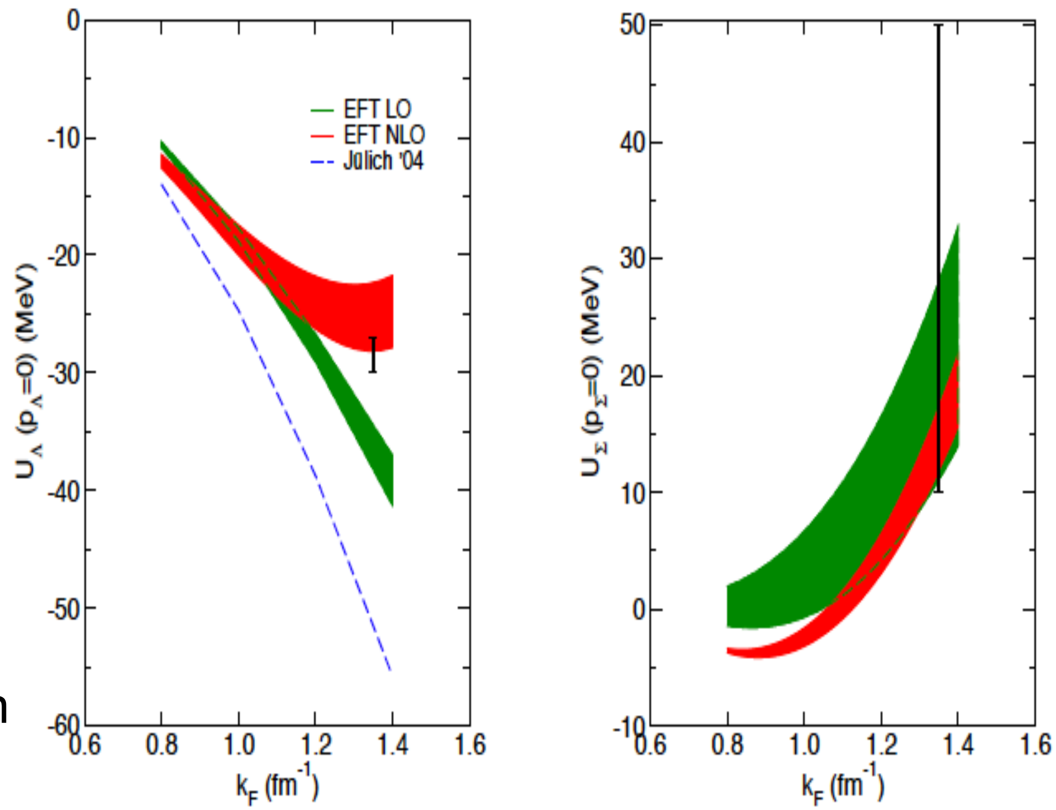
$$G = V + V \frac{Q_{\mathrm{pauli}}}{E_0 - H_0} G$$

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

	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!



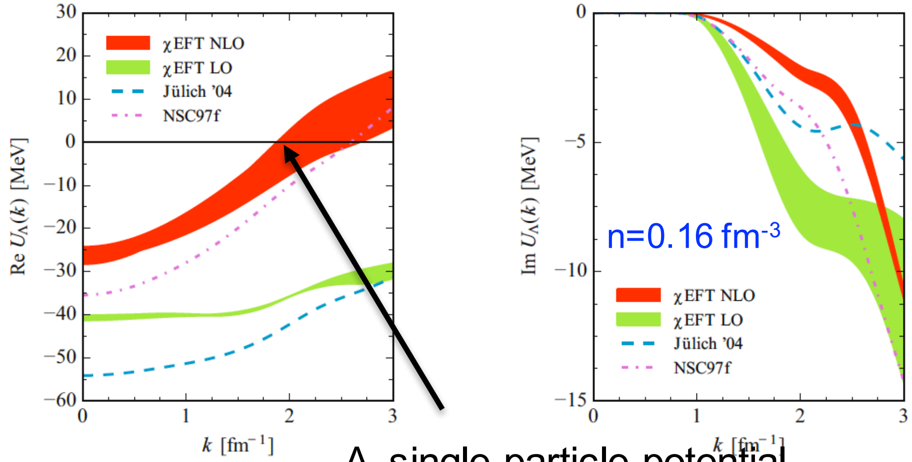
Haidenbauer and Meißner , NPA 936 (2015) 29

* Nemura et al EPJ Web of Conferences 175 (2018) 05030; Hatsuda (HALQCD) SQM2019

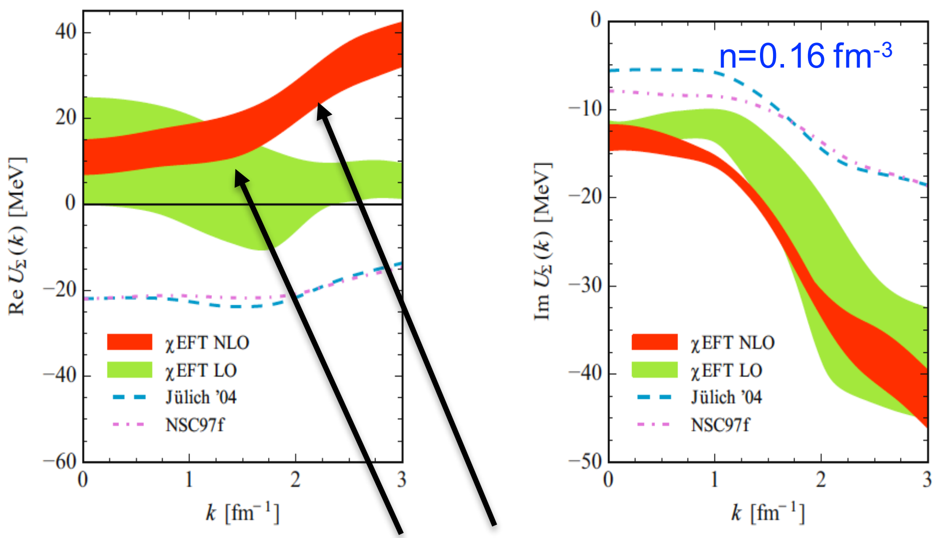
Improving on the calculation by using χEFT NN interaction and continuous choice in Brueckner-Hartree-Fock approach while investigating isospin-asymmetric matter

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

symmetric nuclear matter

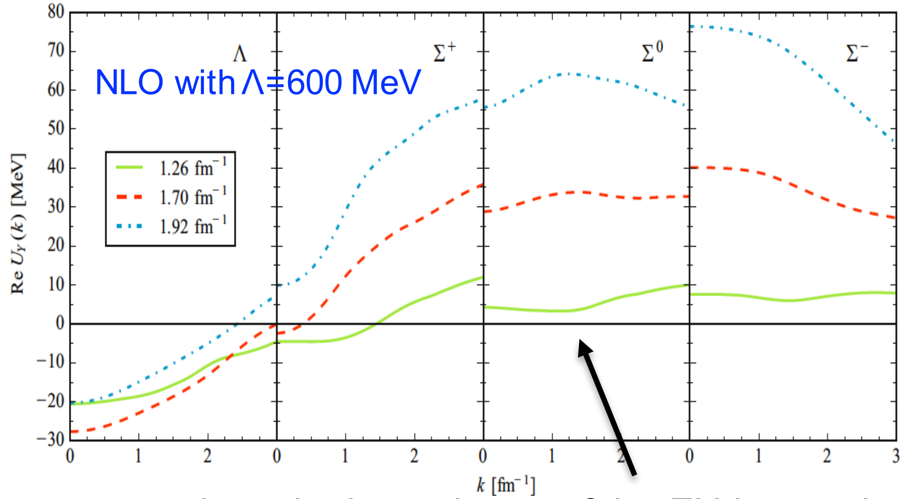


Λ single-particle potential at NLO turns repulsive k~2 fm $^{-1}$

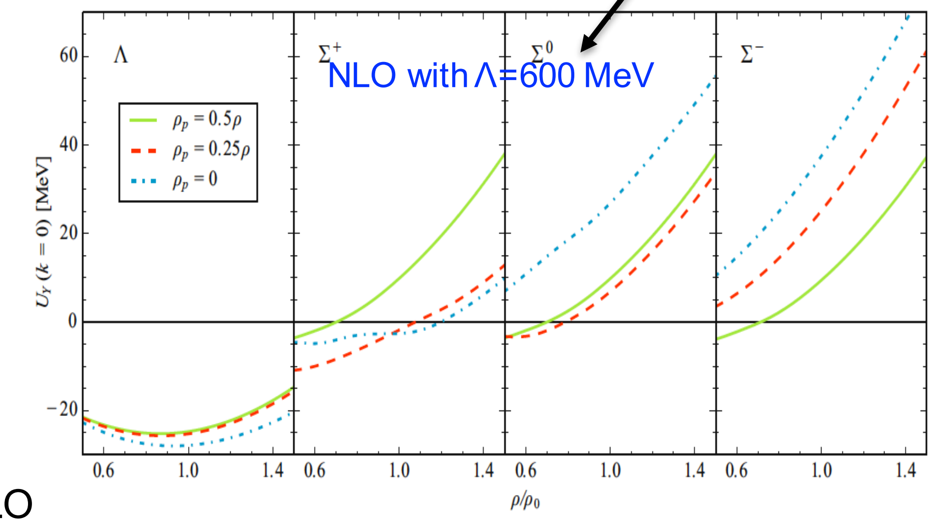


Σ-nuclear potential is moderately repulsive for LO and NLO

neutron matter



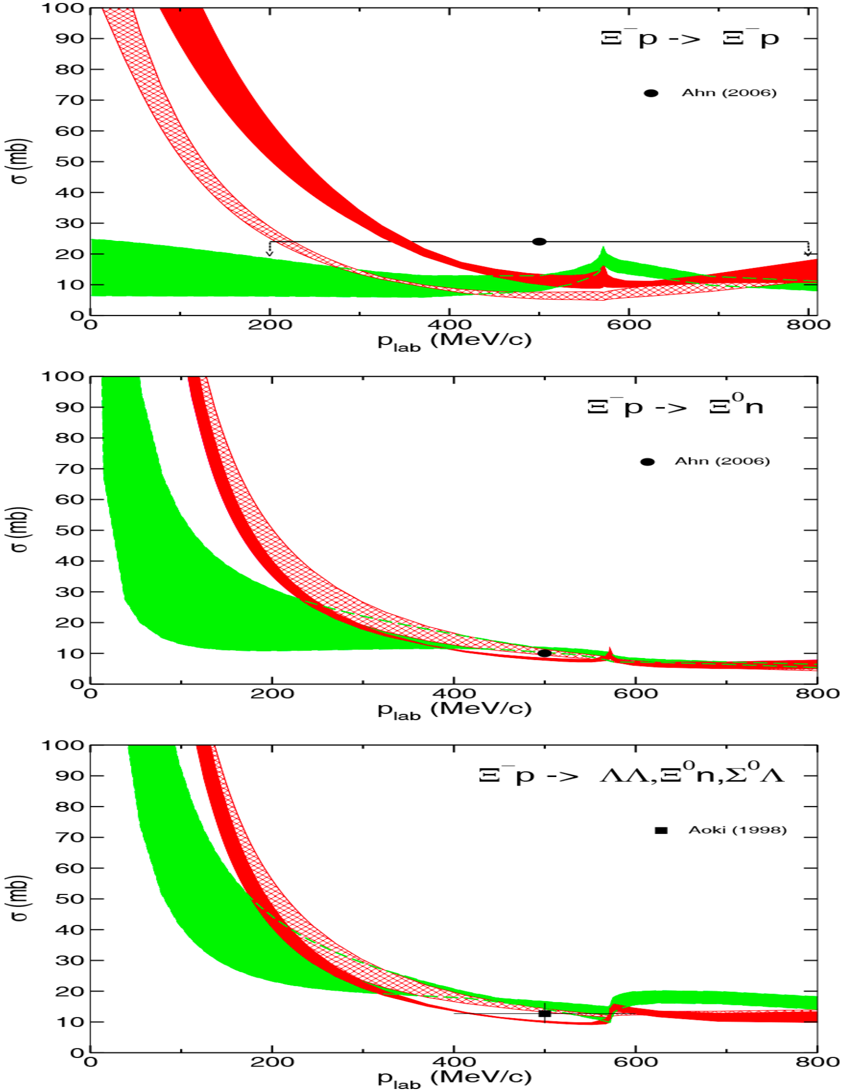
strong isospin dependence of the ΣN interaction



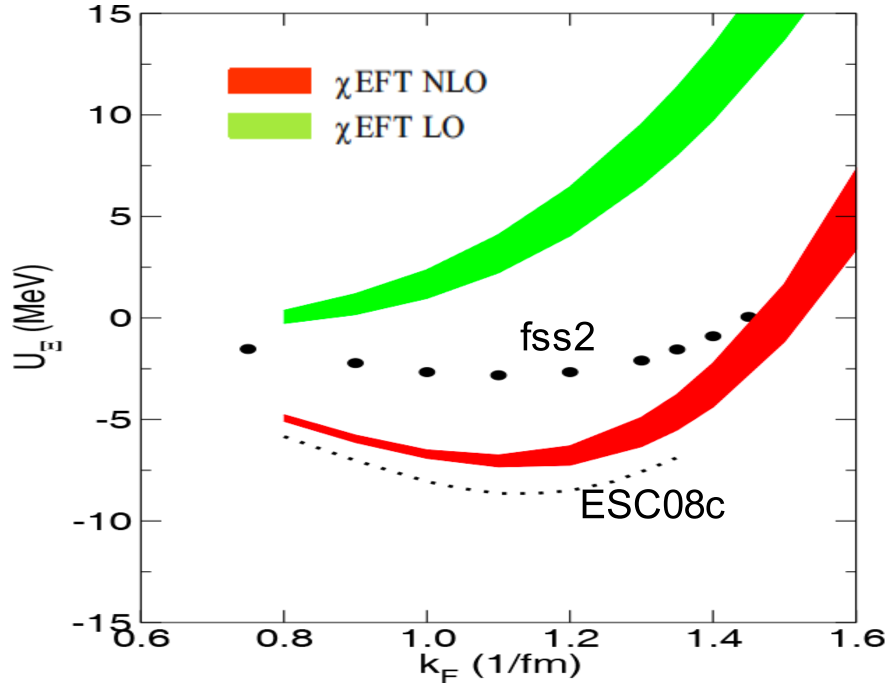
ΞN scattering and Ξ in dense matter

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

Using experimental constraints on ΛΛ scattering length to be mildly attractive, whereas ΞN cross sections are small



Ξ in dense matter

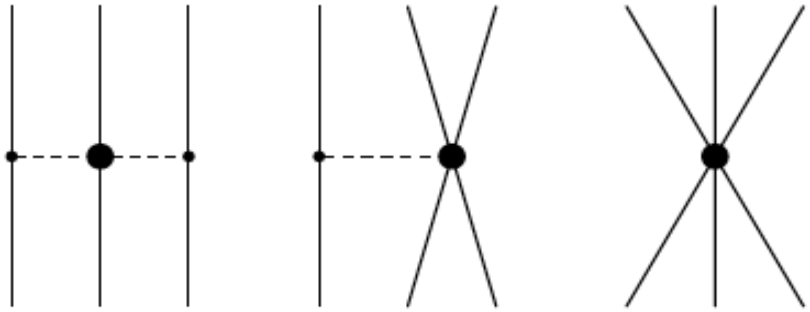


Moderately attractive Ξ-nuclear interaction, with $U_\Xi(0)$ ~ -3 to -5 MeV.
Smaller than $U_\Xi(n_0)$ ~-14 MeV Khaustov et al'00 and in line with other BHF studies with phenomenological ΞN potentials

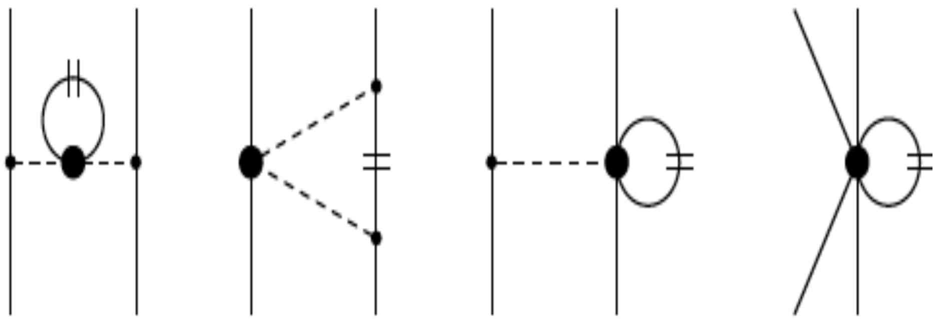
Λ in dense matter: including three-body forces

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

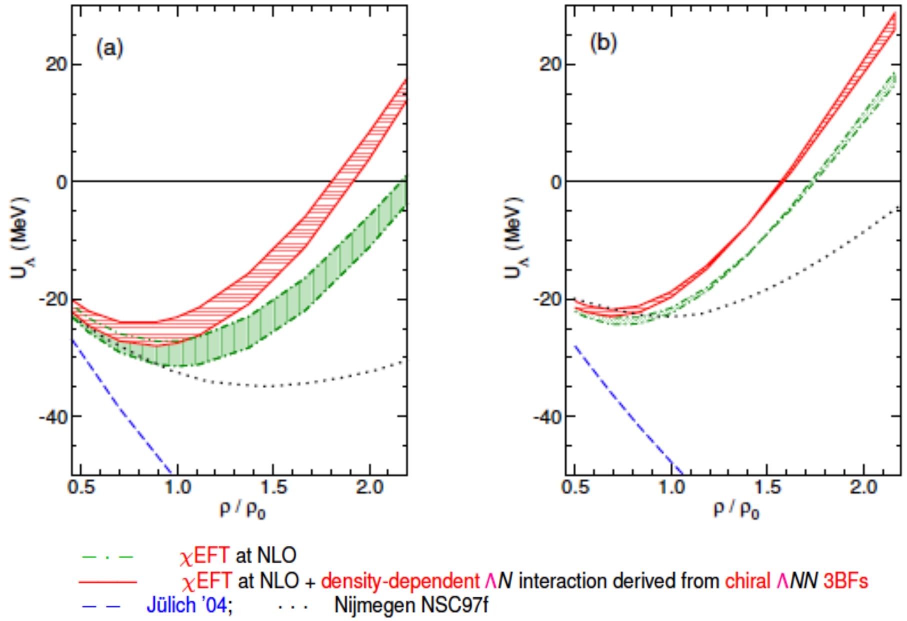


closing two baryon lines summing over the Fermi sea

credit: Haidenbauer

Λ in dense matter

symmetric matter — neutron matter



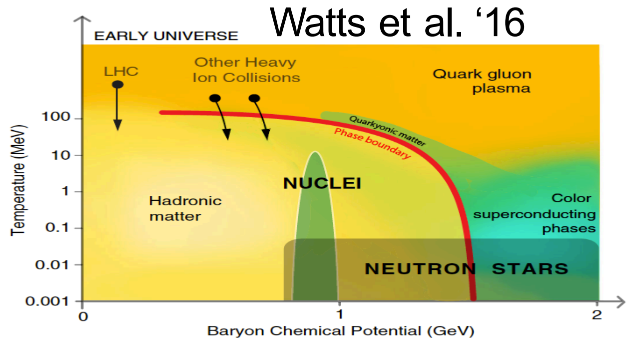
χEFT gives little attraction or even repulsion for $n>n_0$

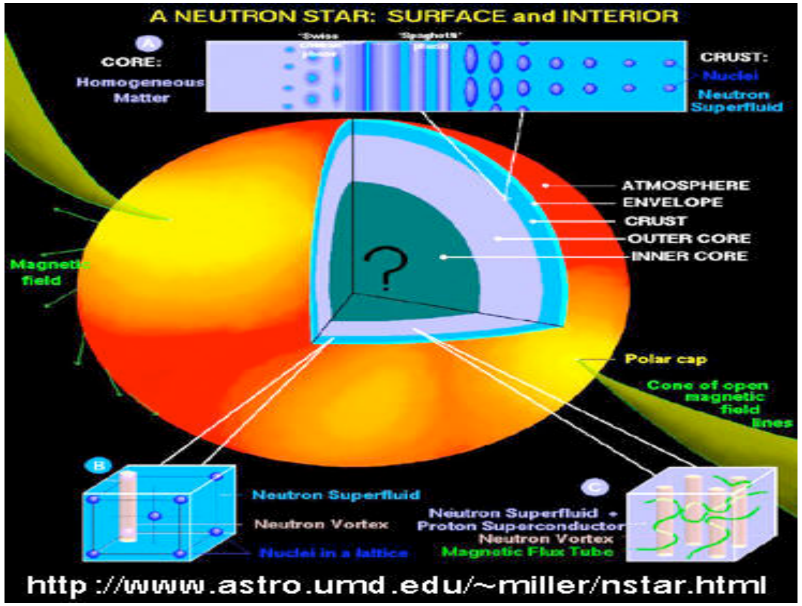
In neutron stars, hyperons will appear at high density!!

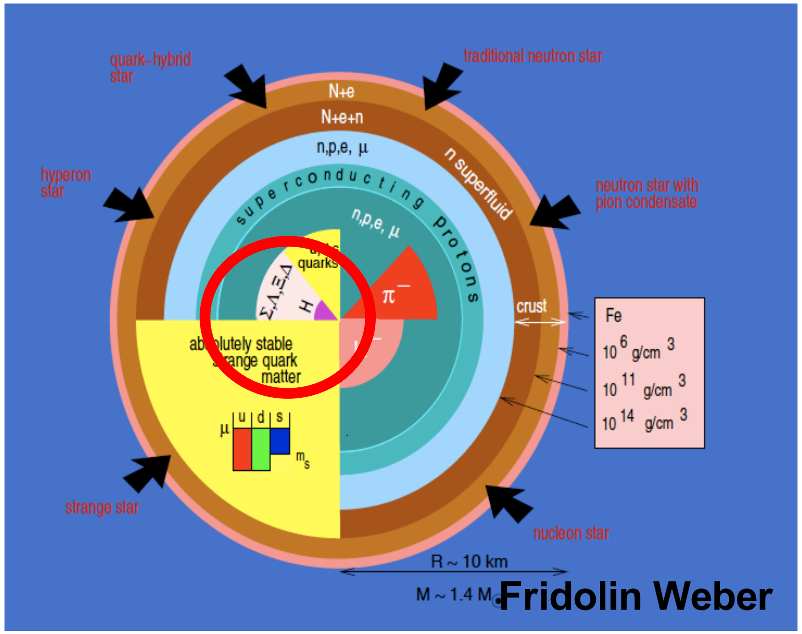
Solution of the Hyperon Puzzle?

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

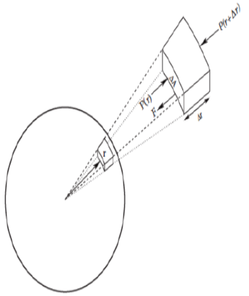
• extreme densities up to 5-10 ρ_0 ($n_0=0.16\ fm^{-3} \Rightarrow \rho_0=3 \bullet 10^{14}\ g/cm^3$)

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

• temperature: $T \sim 10^{\ 6\ldots 11}$ K

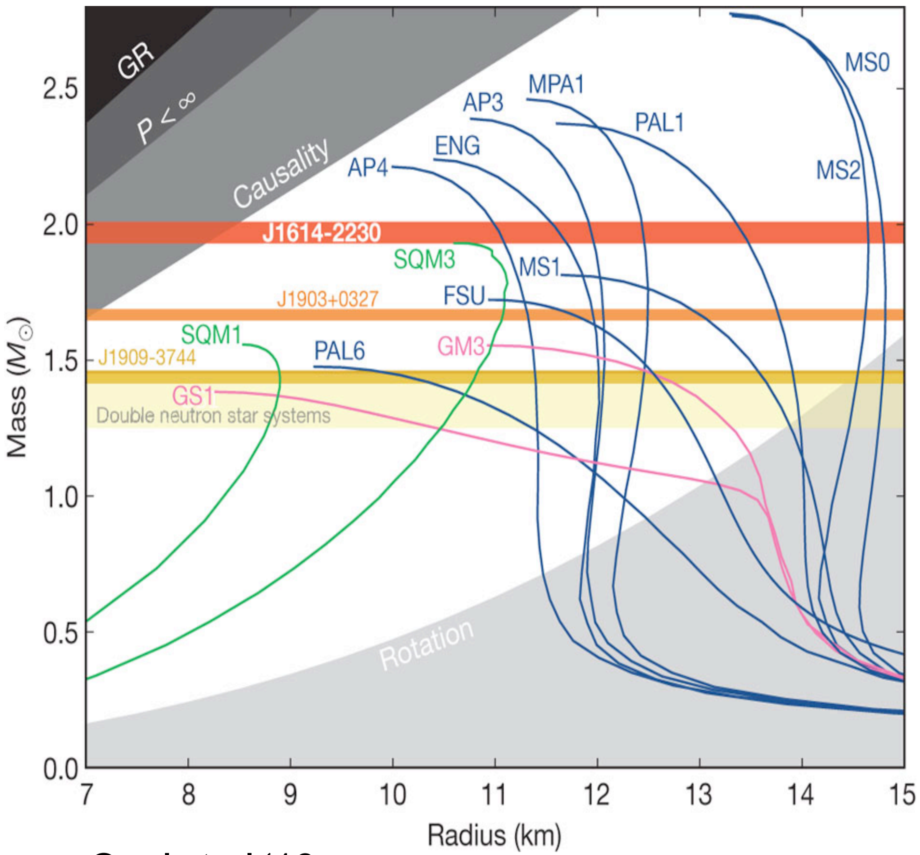
• observations: masses, radius (?), gravitational waves, cooling…

Mass-Radius Relation



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

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



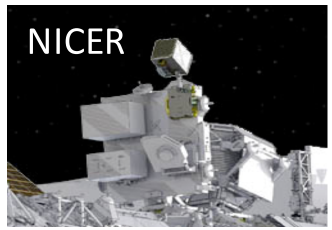
Ozel et al '16

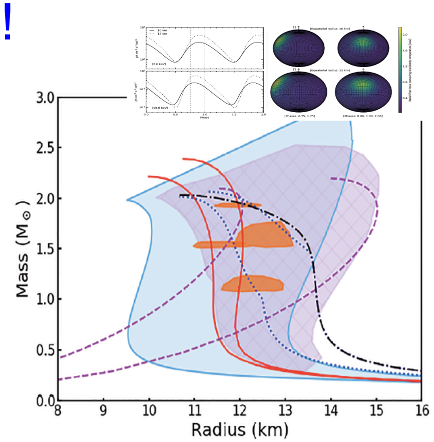
- primary ingredient:

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

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

$$n \to p\, e^-\, \bar{\nu}_e$$

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

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

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

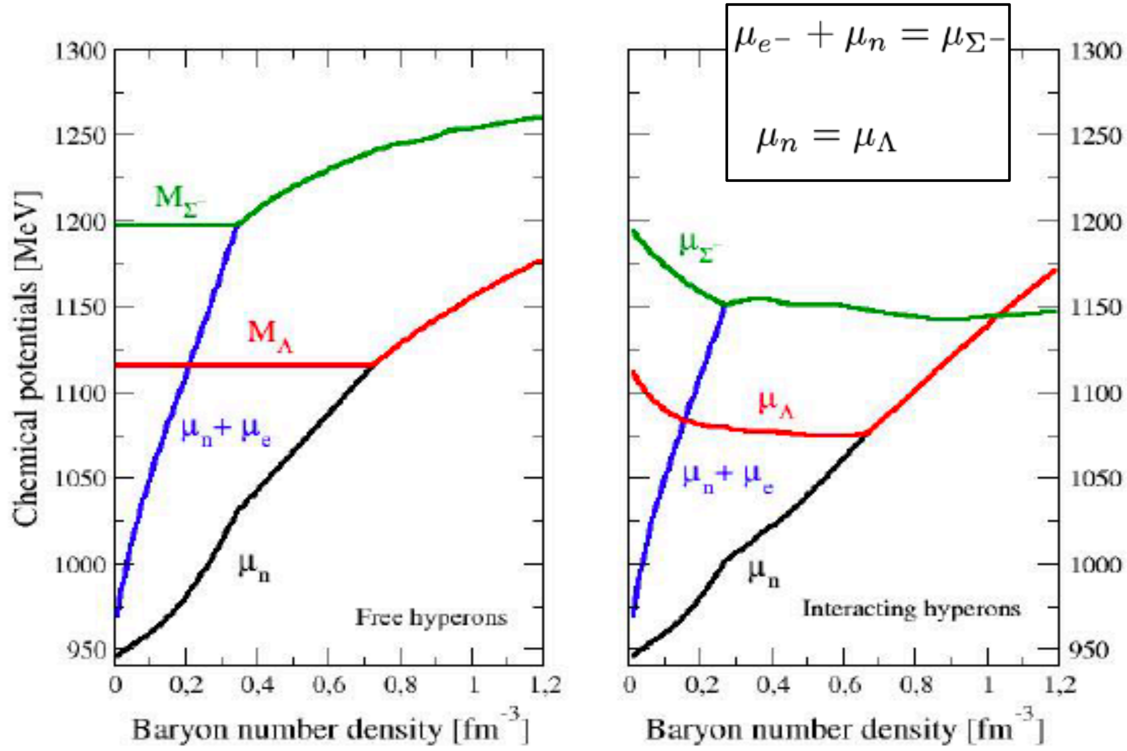
$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

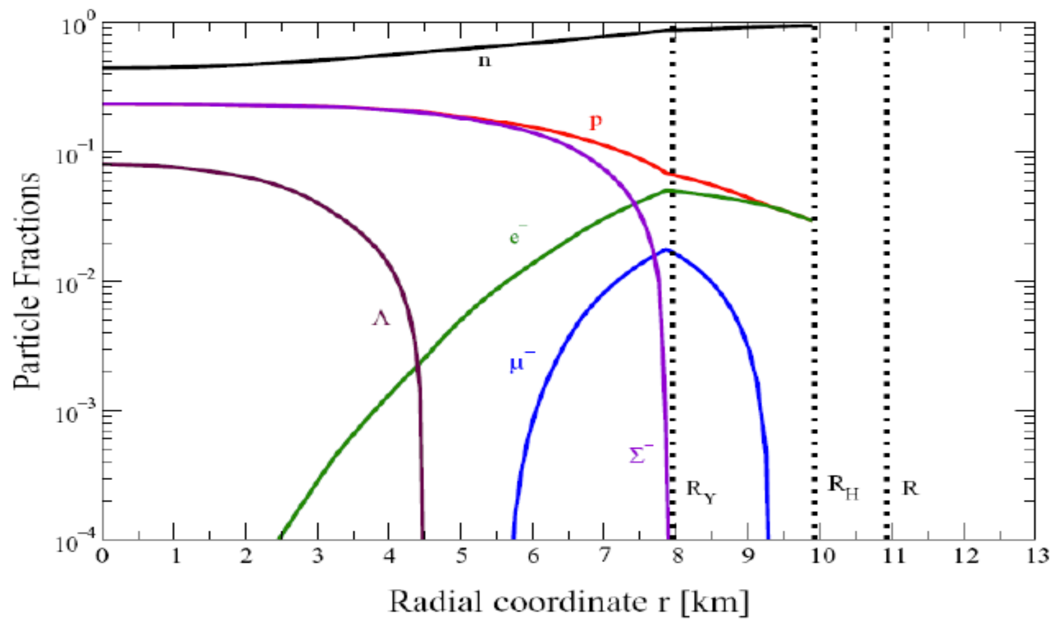
$$n + n \rightarrow p + \Sigma^-$$

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

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

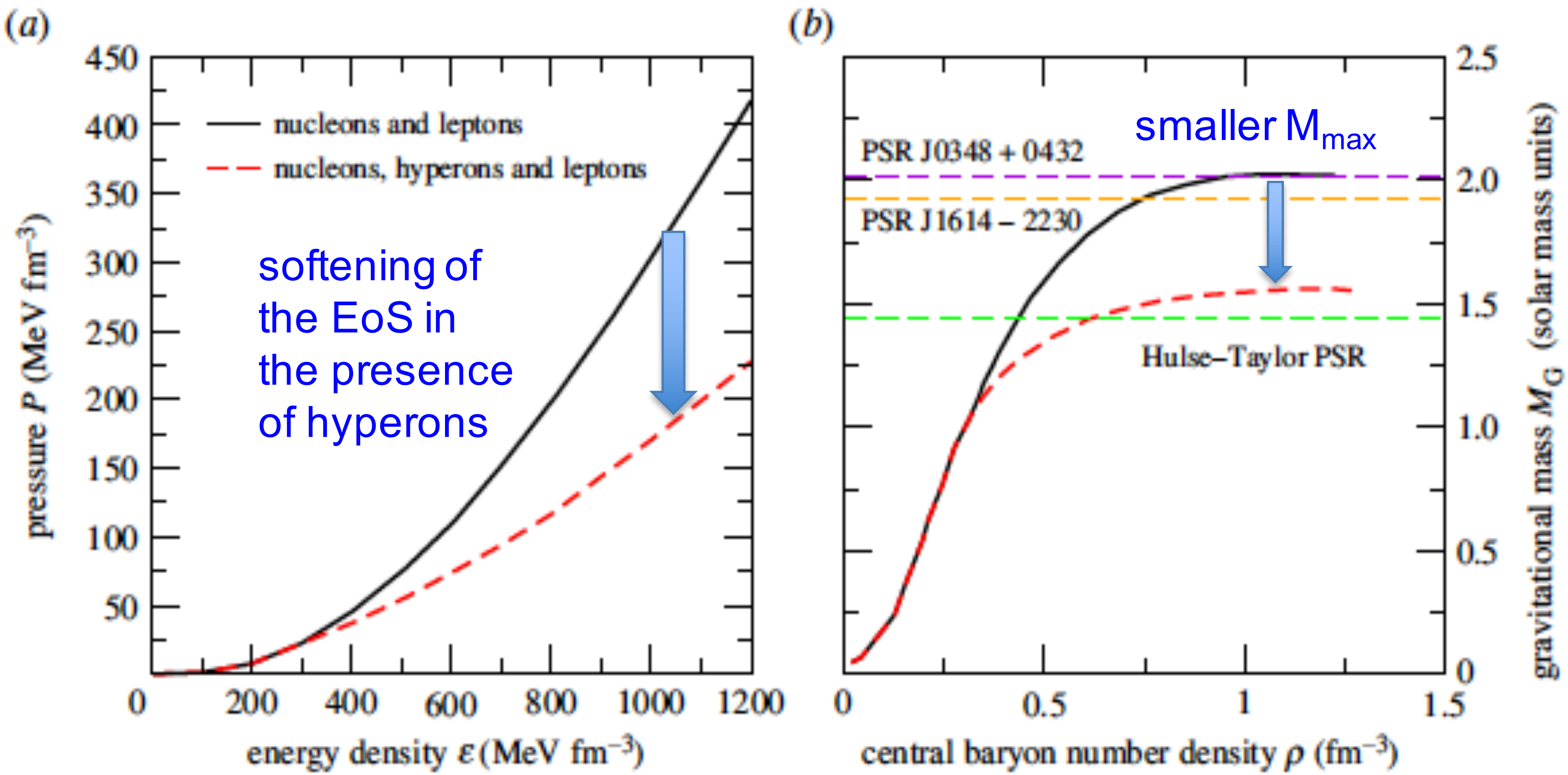
$$\sum_i x_i q_i = 0$$





credit: Vidana

Inclusion of hyperons….

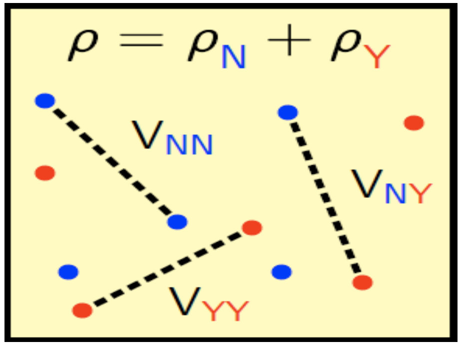


….. induces a strong softening of the EoS that leads to $\mathbf{M_{max} < 2M_{sun}}$

Chatterjee and Vidana, Eur.Phys.J. A52 (2016) 29
Vidana, Proc. Roy. Soc. Lond. A474 (2018) 0145

The Hyperon Puzzle

Experimental Data from YN scattering and hypernuclei



- YN: < 50 scattering data points

- NΛ: Λ-hypernuclei for A=3-209, $U_\Lambda(n_0)$= -30 MeV
- NΣ: Σ^- atoms but no Σ-hypernuclei, $U_\Sigma(n_0)$= 30 MeV ?
- NΞ: one Ξ hypernuclei $U_\Xi(n_0)$= -14/-18/-28 MeV ?
- ΛΛ: few ΛΛ hypernuclear events, slightly attractive ?

- YY with Λ, Σ, Ξ unknown!

Theoretical models for hyperons in neutron stars

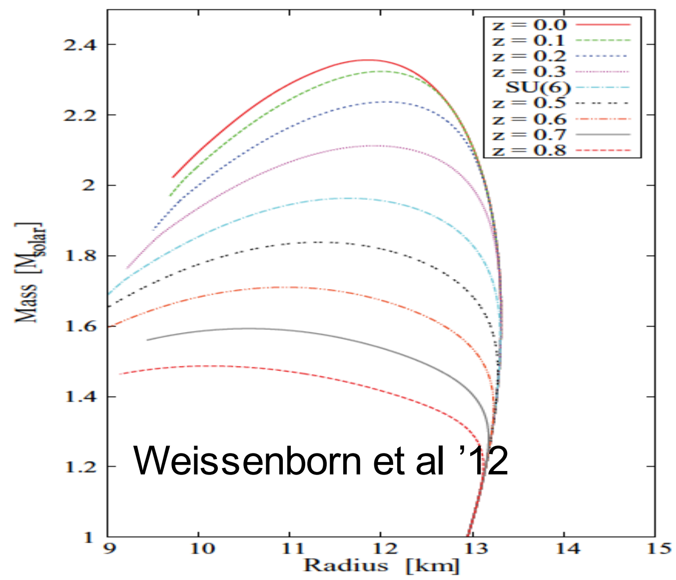
- Relativistic mean field models
Glendenning '85; Knorren, Prakash & Ellis '95; Schaffner & Mishustin '96..
- Non-relativistic potential model
Balberg & Gal '97…
- Quark-meson coupling model
Pal et al '99..
- Chiral effective lagrangians
Hanauske et al. '00…
- Density dependent hadron field model Hofmann, Keil & Lenske '01..
- DBHF/BHF approaches
Brockmann & Machleidt '90; Baldo, Burgio,Schulze '00; Vidana et al. '00; Jong and Lenske '98..
- Low-momentum interactions
Schwenk, Pethick, Hebeler, Friman, LT, Djapo..
- Quantum Montecarlo
Leonardi et al '14..

Solutions to the Hyperon Puzzle?

I. Stiffer YN and YY interactions

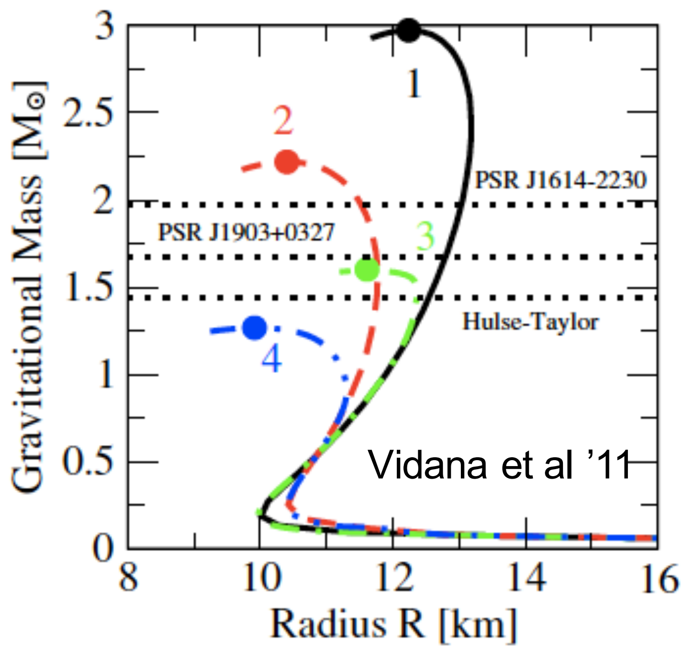
mainly explored in RMF models:
coupling of ϕ to hyperons to shift the onset of hyperons to higher densities
Bednarek et al '12; Weissenborn et al '12;
Oerte et al '15; Maslov et al '15..

results still compatible with $\Delta B_{\Lambda\Lambda}(^6He_{\Lambda\Lambda})$
Fortin et al '17



II. Hyperonic 3-body forces

not yet a general consensus:
while for some models 2Msun are reached,
Taktasuka et al '02 '08; Yamamoto et al '13 '14..
for others M_{max} is $1.6M_{sun}$ Vidana et al '11
while Lonardoni et al '15
shows no a conclusive outcome due to the strong dependence on ΛNN force

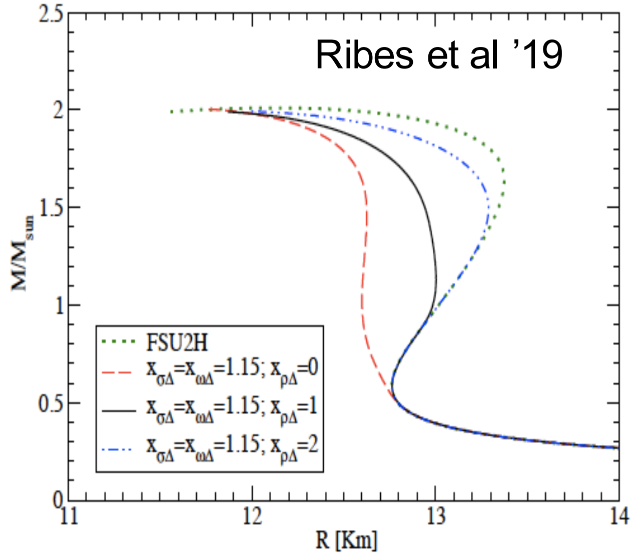


Solution from point of view of χEFT!!

Solutions to the Hyperon Puzzle?

III. Push of Y onset by Δ-isobars or meson condensates

appearance of another degree of freedom that push Y onset to higher densities.
It might (or not) reach $2M_{sun}$



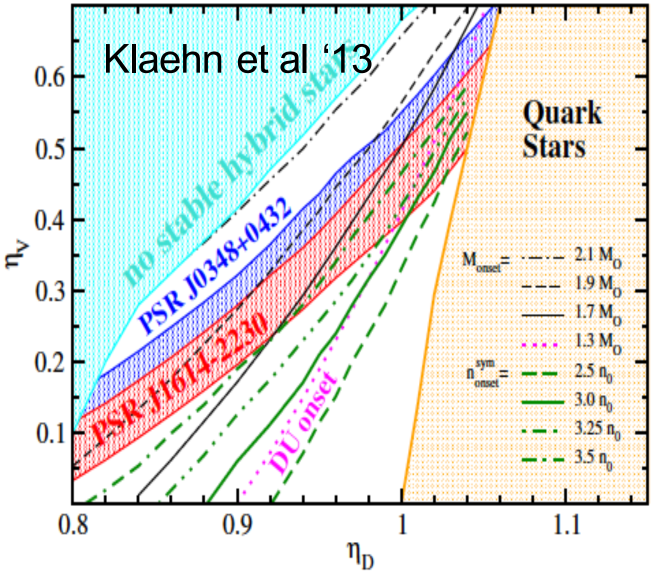
Δ
Drago et al '14 '15, Jie Li et al '19 ; Ribes et al '19…

K condensate
Kaplan et al' 86, Brown et al '94; Thorsson et al '94; Lee '96; Glendenning et al '98..

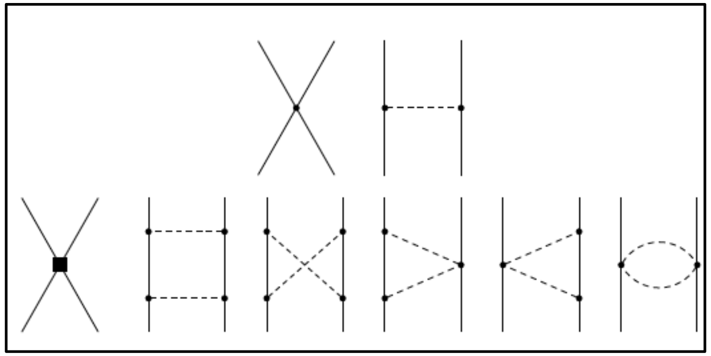
IV. Quark matter below Y onset

early transition to quark matter below Y onset, with quarks providing enough repulsion to reach $2M_{sun}$

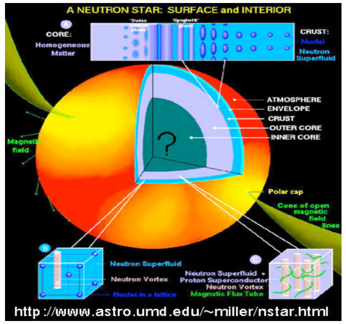
Weissenborn et al '11; Klaehn et al '13;
Bonanno et al '12; Lastowiecki et al '12…



V. Others: modified gravity...



Summary



- We have presented the YN and YY interactions in dense matter for different approaches and, in particular, for χEFT

- Λ, Σ and Ξ interactions in nuclear matter have been investigated from χEFT at NLO (and with density-dependent 2-body forces for ΛNN), showing attraction for Λ, and repulsion for Σ and Ξ at low densities

- Λ feels little attraction or even repulsion for $n>n_0$ in χEFT, pointing to a possible solution of the Hyperon Puzzle in neutron stars

- We have discussed the presence of hyperons in neutron stars and the possible solutions to the Hyperon Puzzle