HYP 2022 PRAGUE
14th International Conference on Hypernuclear and Strange Particle Physics
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Strange Mesons in Nuclei and Neutron Stars

Institute of Space Sciences
CSIC IEEC
Consejo Superior de Investigaciones Científicas

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FIAS Frankfurt Institute for Advanced Studies

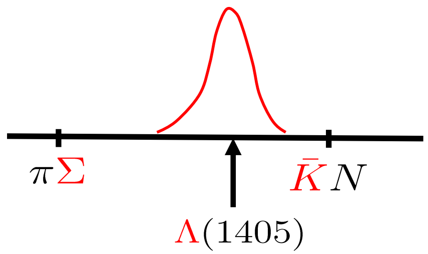
(partially based on)
Laura Tolos and Laura Fabbietti,
Prog. Part. Nucl. Phys. 112 (2020) 103770, 2002.09223 [nucl-ex]

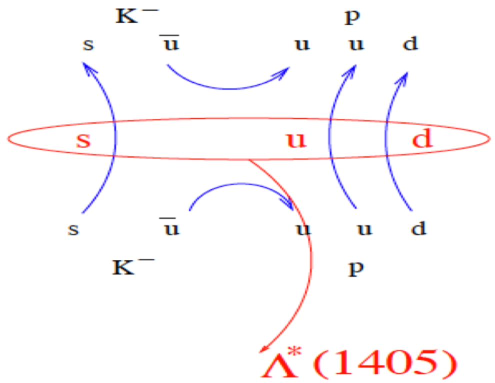
- $\bar{K}$N interaction: Λ(1405) resonance
- $\bar{K}$NN bound state
- Antikaons in matter
- Experiments and observations: from HICs to stars
- Present and Future

$\bar{K}$N interaction: the Λ(1405)

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

- $\bar{K}$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..

talk by Angels Ramos
talks on
Session IV on Monday
Session I on Friday

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)

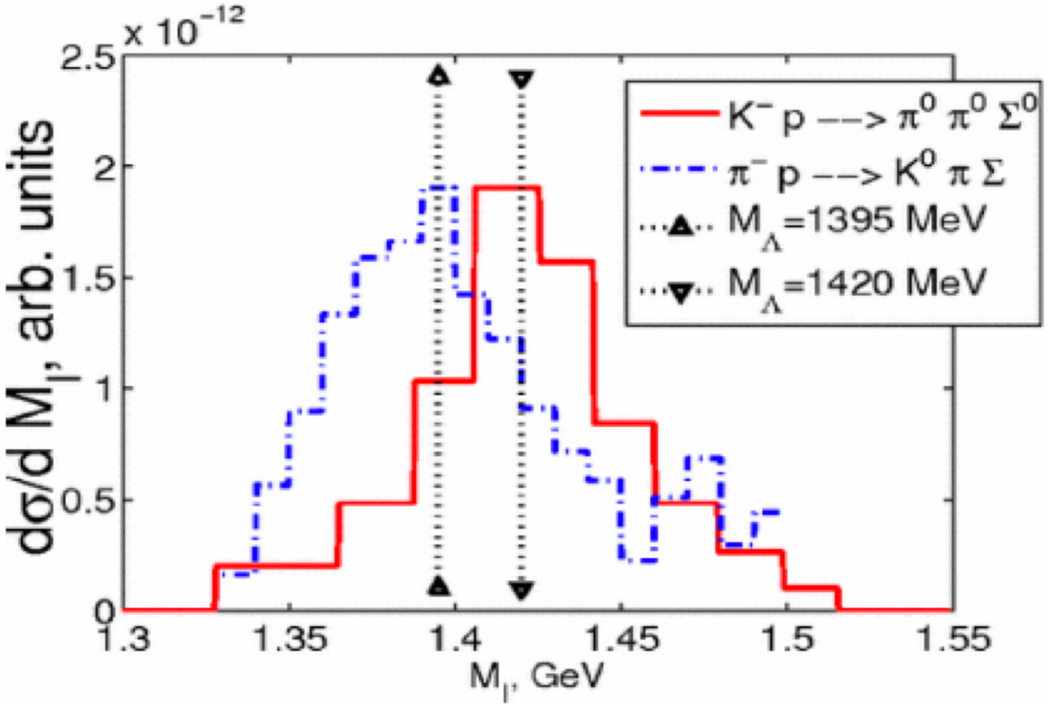
Λ(1405) results from the superposition of two poles in the complex plane,
with different coupling to πΣ and K̄N states

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

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		$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$



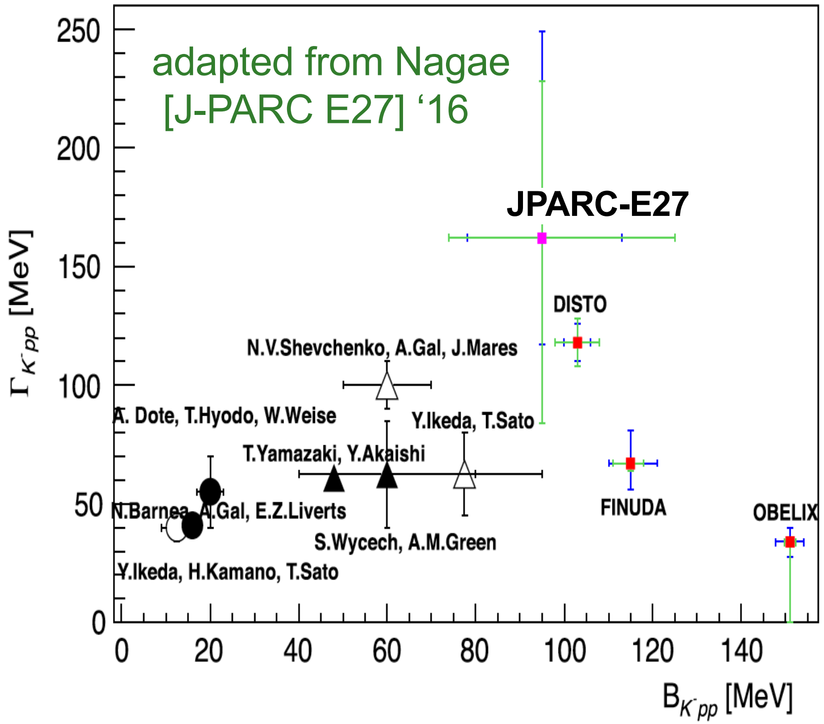
the measured spectra of the Σπ final states associated to the Λ(1405) for kaon- and pion-induced reactions supports the double-pole structure of the Λ(1405)

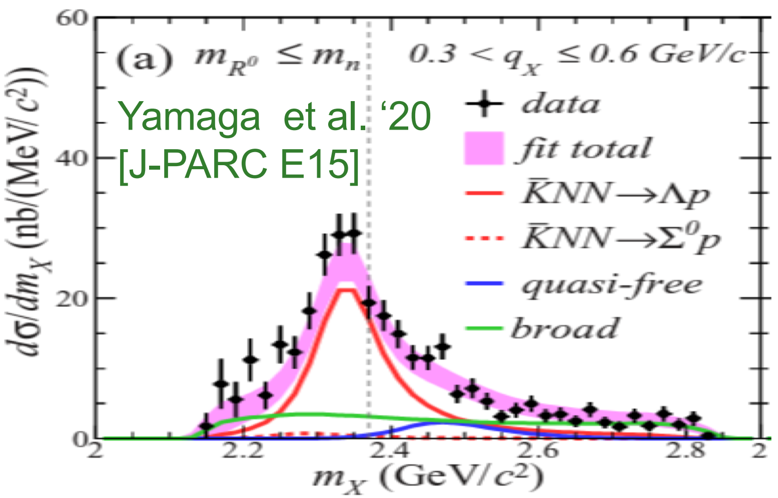
Magas, Oset and Ramos '05

$\bar{K}$NN bound state

talks by
Hyodo, Yamaga

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)

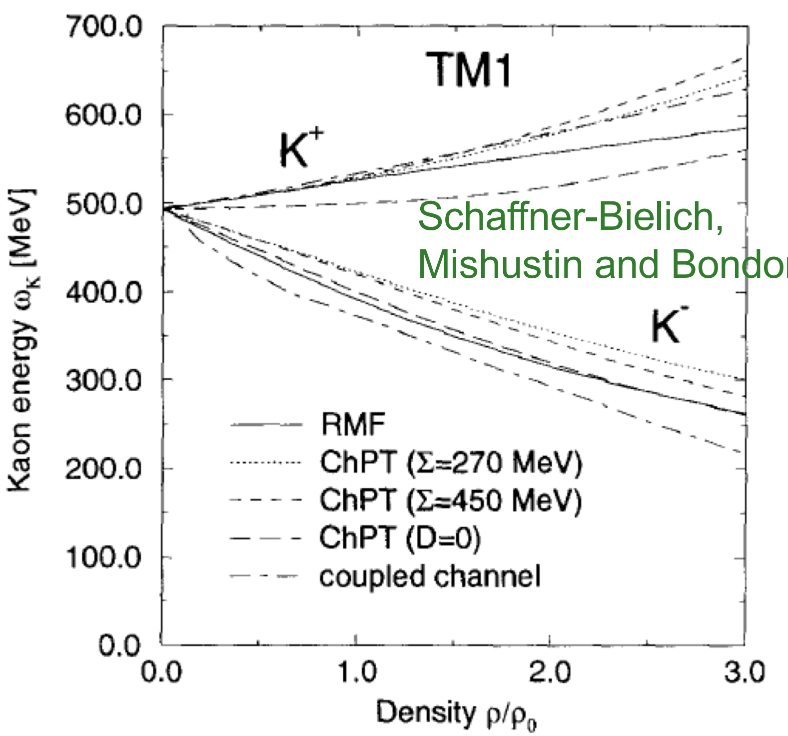
- use of variational or Faddeev calculations introduces certain approximations

(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

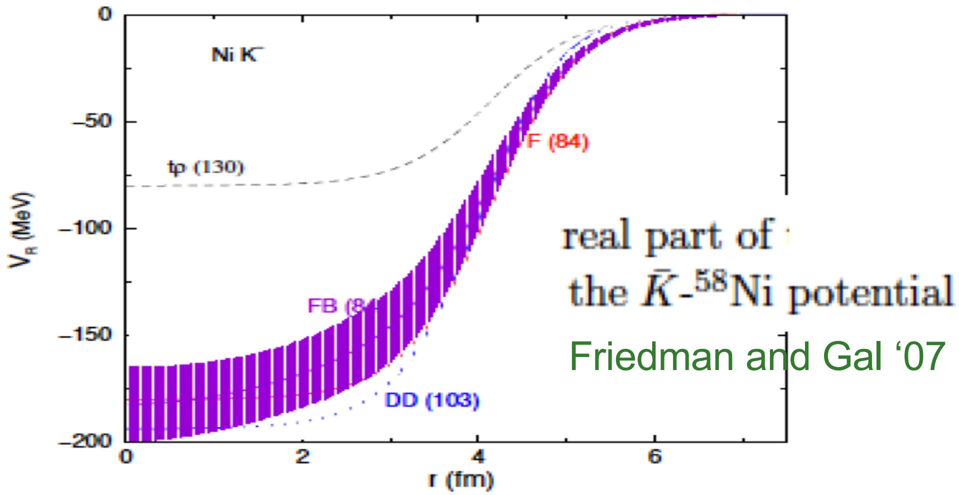
Antikaons in matter

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



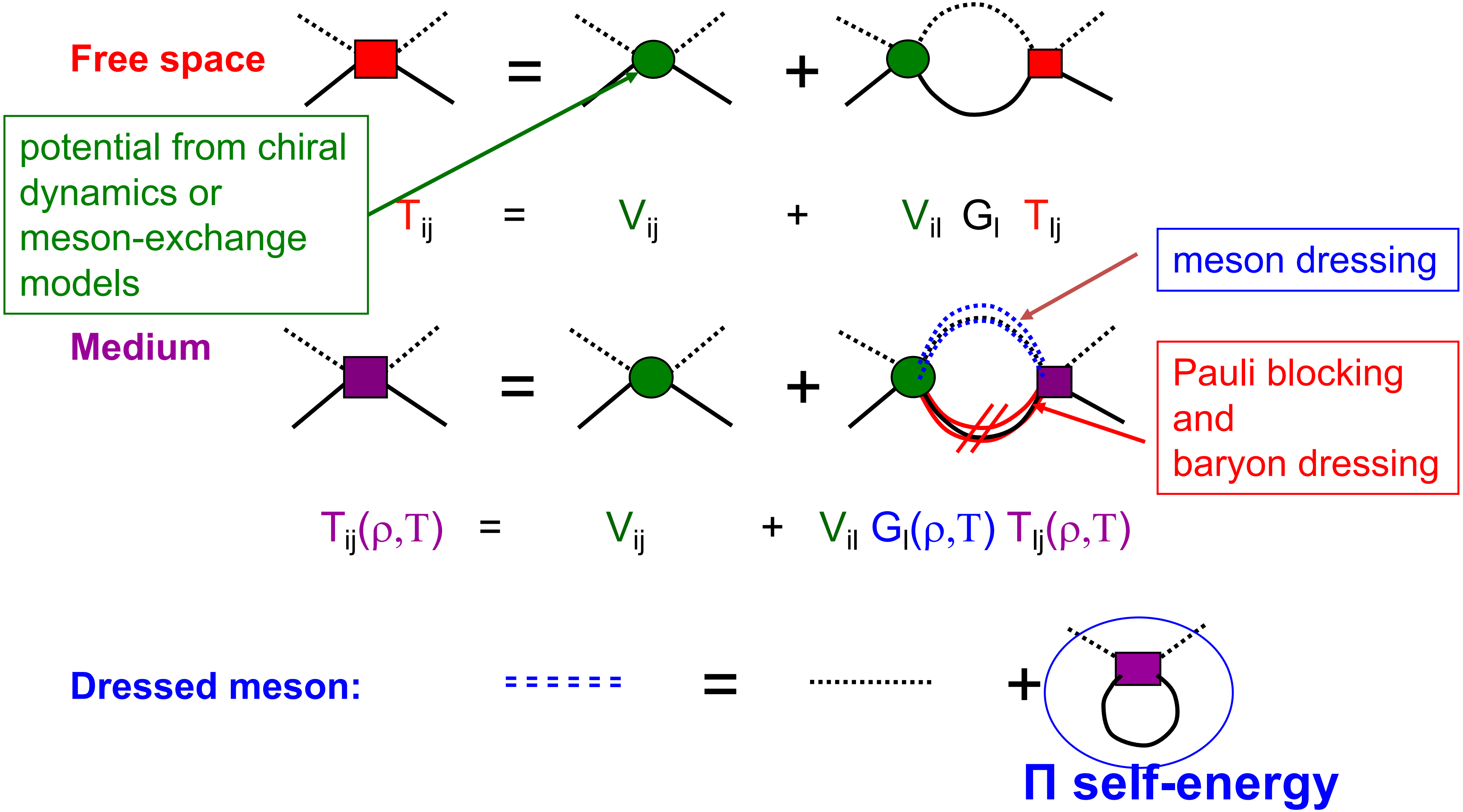
$U_{K-}(\rho_0)$ ~ -100 to -200 MeV

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



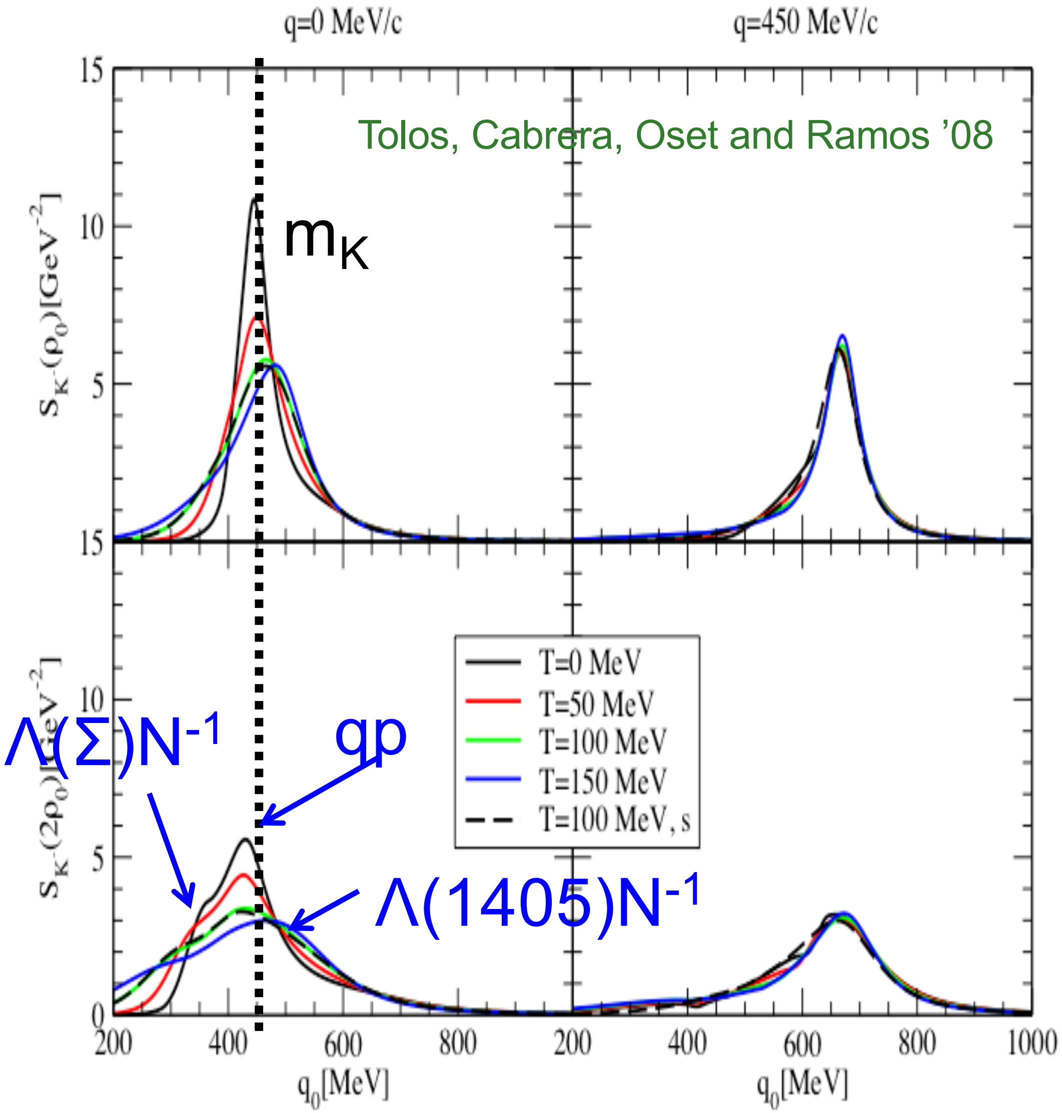
$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

$$T_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, T_{lj}(\rho,T)$$

$\bar{K}$ 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

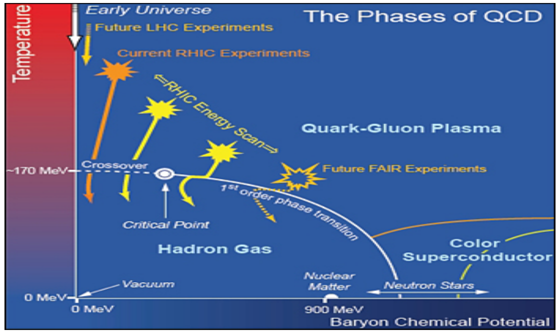
Im $U_{K^-}(\rho_0) \gtrsim$ Re $U_{K^-}(\rho_0)$

- **s-wave** $\bar{K}$N interaction governed by Λ(1405): attraction due to modified Λ(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: $K^*(892)^0$, $\phi(1020)$, $\Sigma^{+-}(1385)$, $\Xi(1530)^0$..

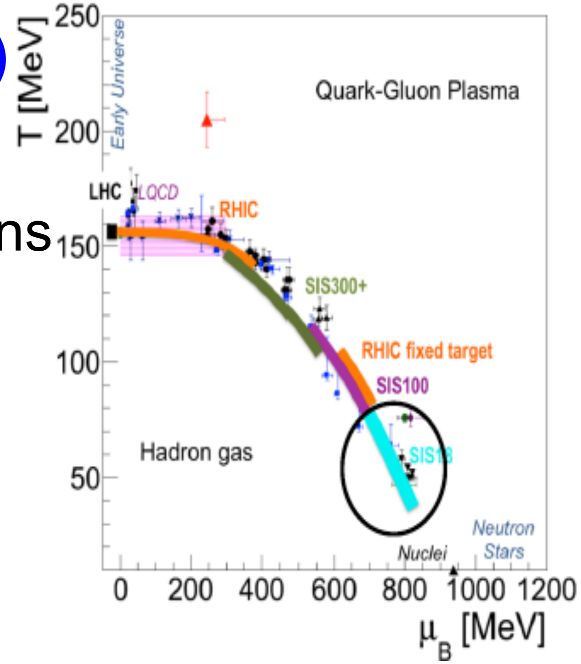
Adams et al. (STAR) '05
Aggarwal et al (STAR) '11
Kumar et al (STAR) '15
Abelev (ALICE) '15
Adam (ALICE) '16
Badala (ALICE) '17..

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

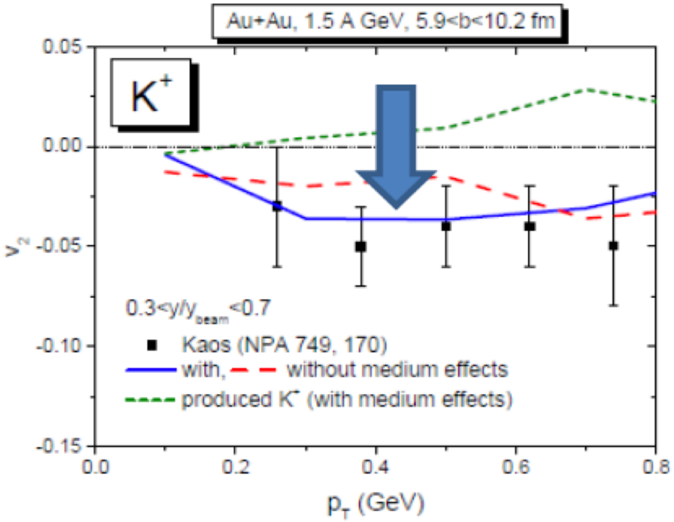
- The nuclear effects on (anti)kaon are more prominent in the collision of large nuclei

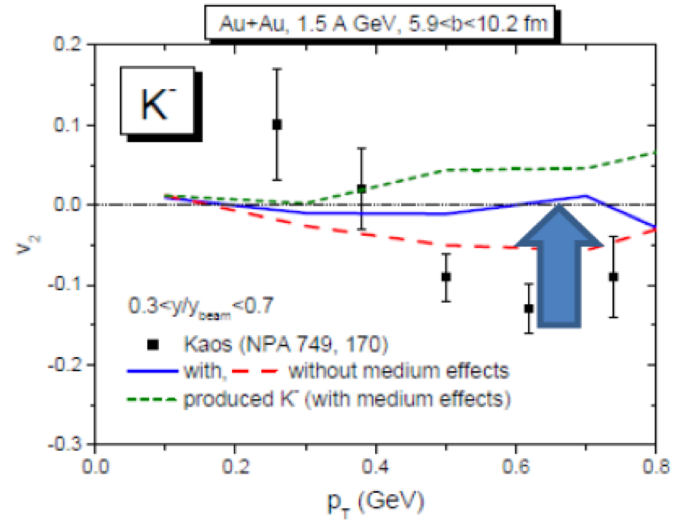
- (Anti)kaon production is (enhanced)suppressed due to (broadening of spectral function)repulsive kaon potential

- (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

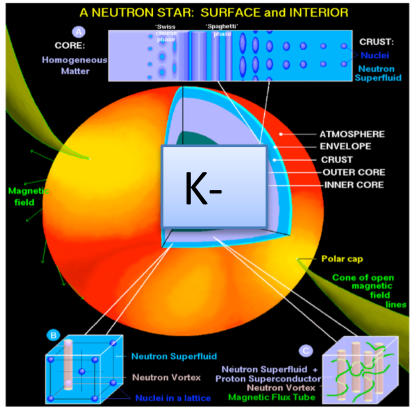
- A moderate EoS (K~300 MeV) reproduces the experimental HiC data better





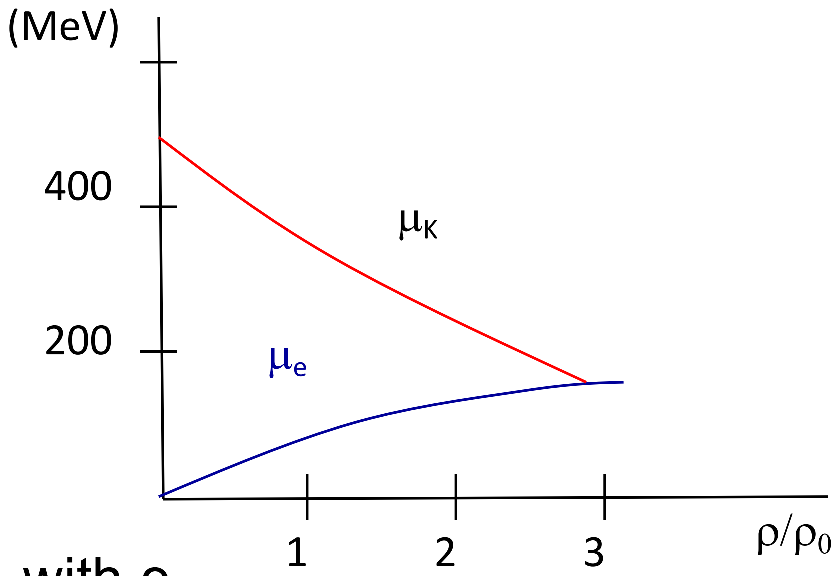
Song, LT, Wirth, Aichelin and Bratkovskaya '21

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

Glendenning '85

Kaon condensation irrelevant as (anti)kaons have to lower their mass drastically

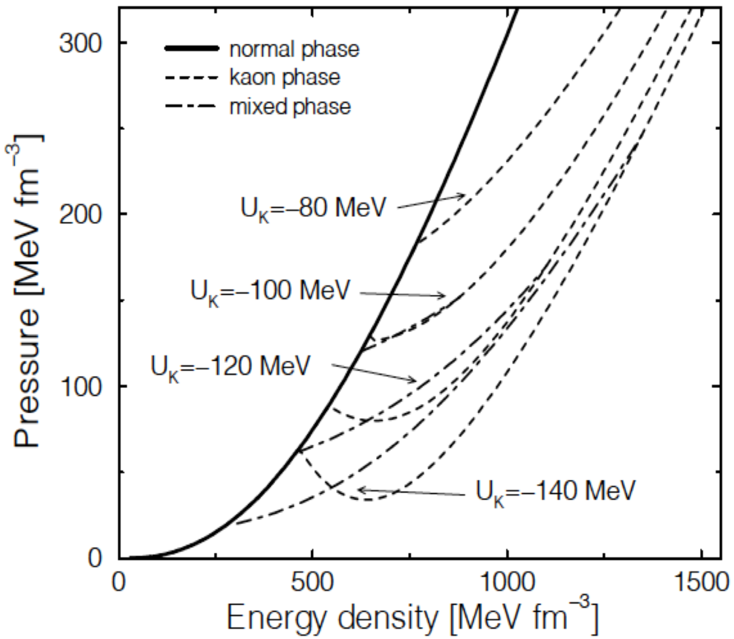
Kaplan and Nelson '86

In-medium effects on (anti)kaons can be pronounced so as to have kaon condensation

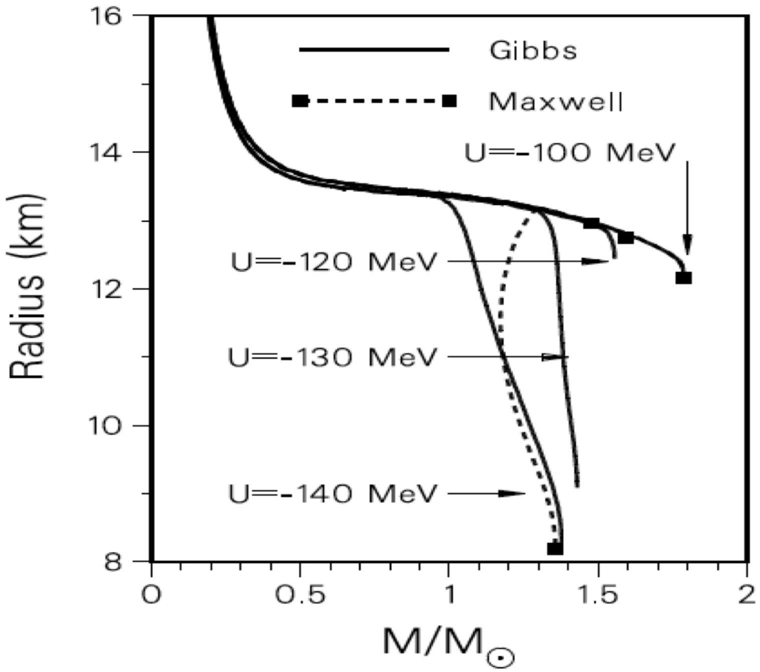
Brown, Kubodera, Rho and Thorsson'92; Thorsson, Prakash and Lattimer '94; Fujii, Maruyama, Muto and Tatsumi '96; Li, Lee and Brown '97; Knorren, Prakash and Ellis '95; Schaffner and Mishustin '96; Glendenning and Schaffner-Bielich '98 '99

Renewed interest on antikaon-nucleon interaction with effective field theoretical models

Glendenning and Schaffner-Bielich '99



EoS is softened
due to kaon condensation



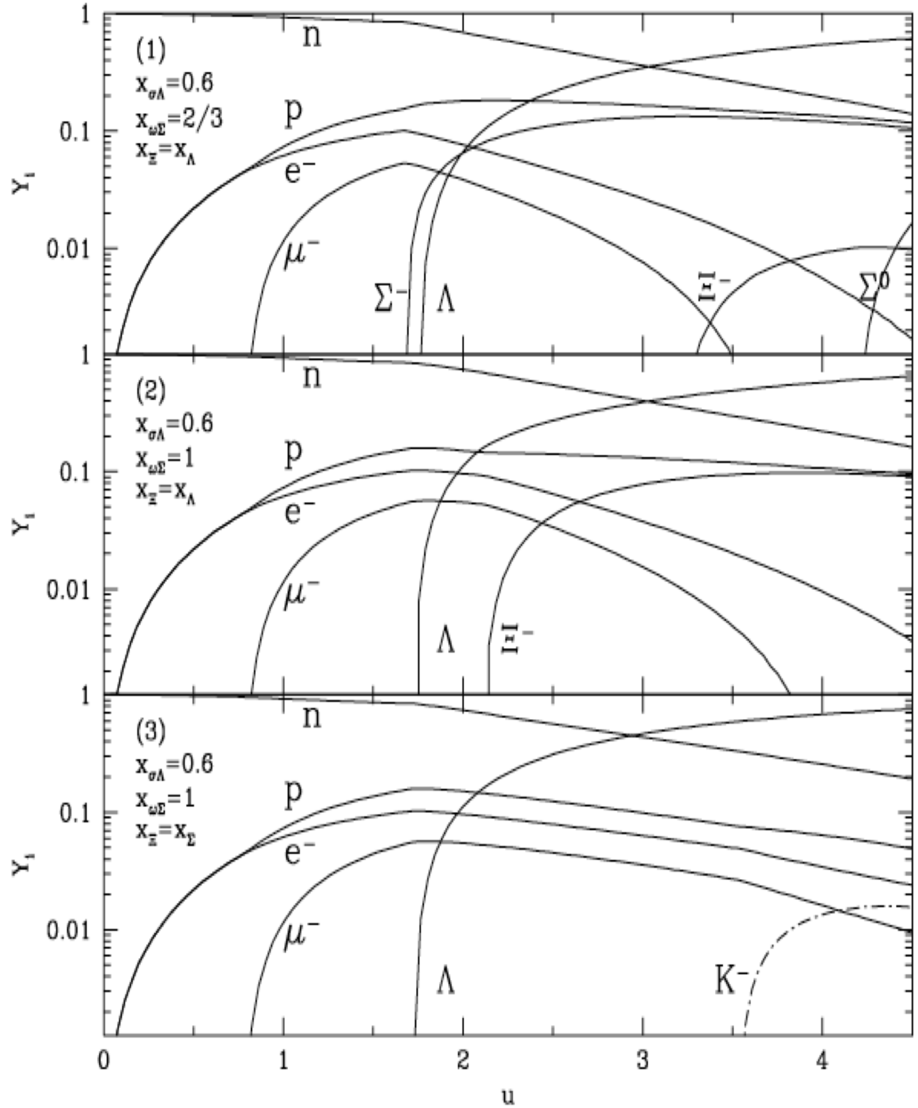
The maximum mass is lowered with increasing attractive K^-N potential

Knorren, Prakash and Ellis ’95

Effects of hyperonization on kaon condensation

Knorren, Prakash and Ellis ’95

electron fraction decreases once hyperons appear, thus, the presence of hyperons increases the critical density for kaon condensation

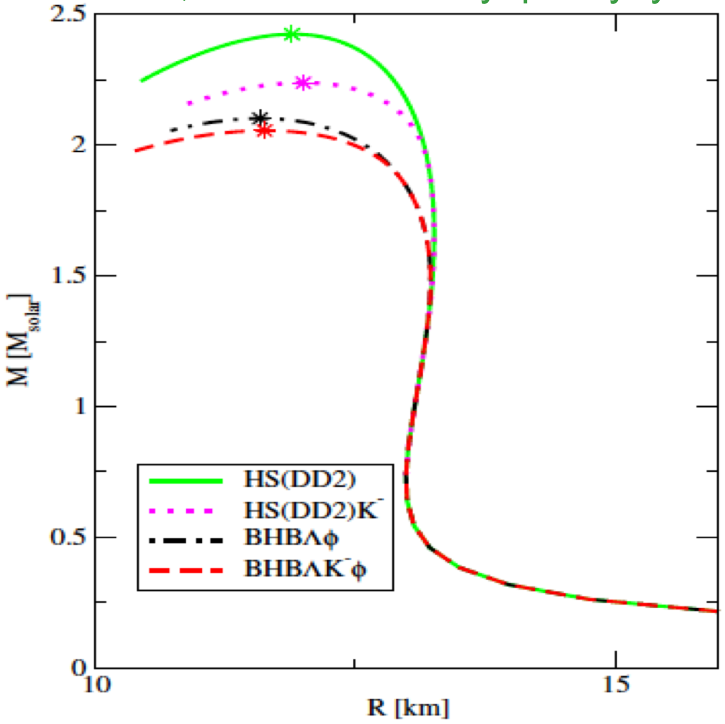


Later on different groups have worked on improved relativistic-mean field models so as to fulfill $2M_{sun}$ neutron star mass observations and, in some cases, to study proto-neutron stars, core-collapse supernova or neutron star mergers

Banik and Bandyopadhyay ’01 ‘02
Char and Banik ‘14
Malik, Banik and Bandyopadhyay ’20 ‘21

RMF effective model with density-dependent couplings for nucleons and hyperons, and kaon condensate

Malik, Banik and Bandyopadhyay ‘21

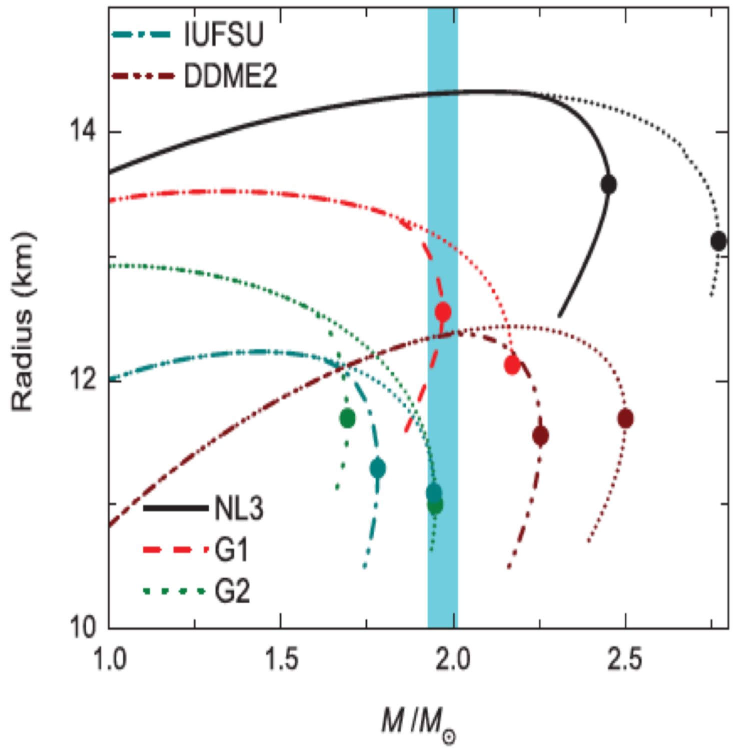


Antikaon potential at saturation density deeper than -120 MeV

Gupta and Arumugam ‘12 ‘13

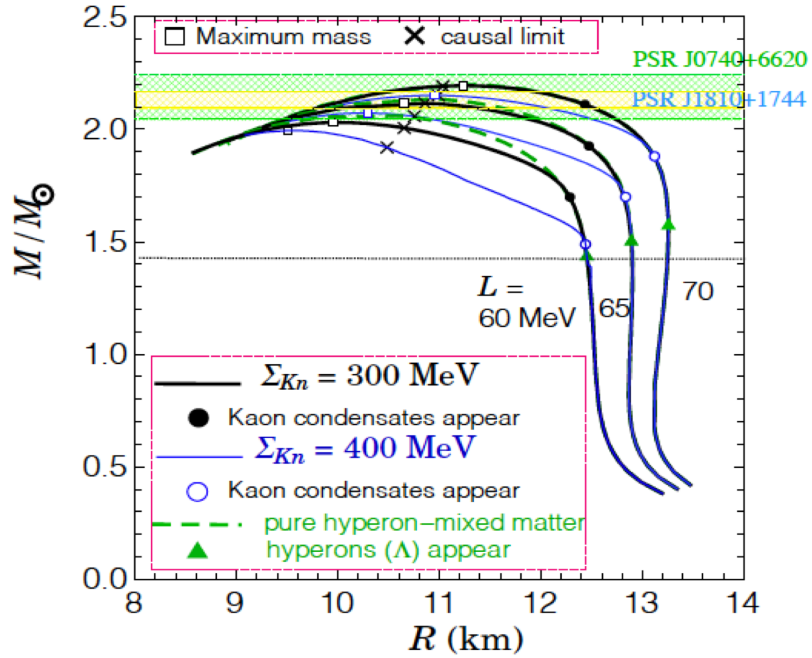
RMF effective models with higher-order couplings for nucleons, and kaon condensate. No hyperons are considered

Gupta and Arumugam ‘13



Antikaon potential at saturation density is deeper than -140 MeV

Muto, Maruyama and Tatsumi ‘21



Muto ‘08
Muto, Maruyama, Tatsumi and Takatsuka ’19
Muto, Maruyama and Tatsumi ’21

RMF effective model for hyperons and kaon condensate with repulsive three-body forces (SJM) including or not TNA

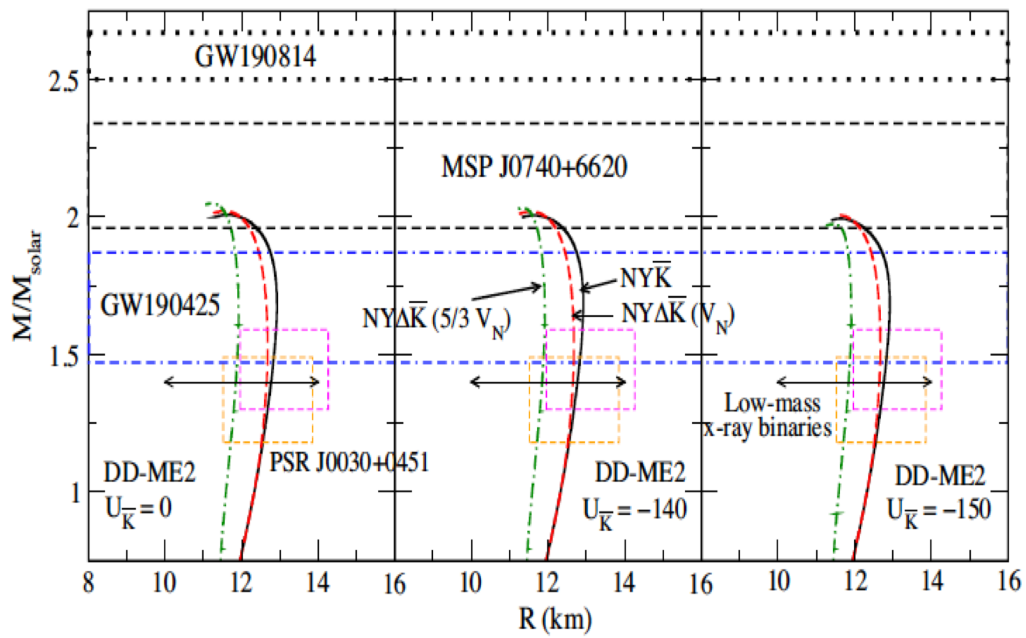
Antikaon potential at saturation density is deeper than - 100 MeV

Thapa and Sinha ‘20
Thapa, Sinha, Li and Sedrakian ‘21

RMF model (CDF model) for nucleons and kaon condensate; or for nucleons, hyperons, *Δ* and kaon condensate

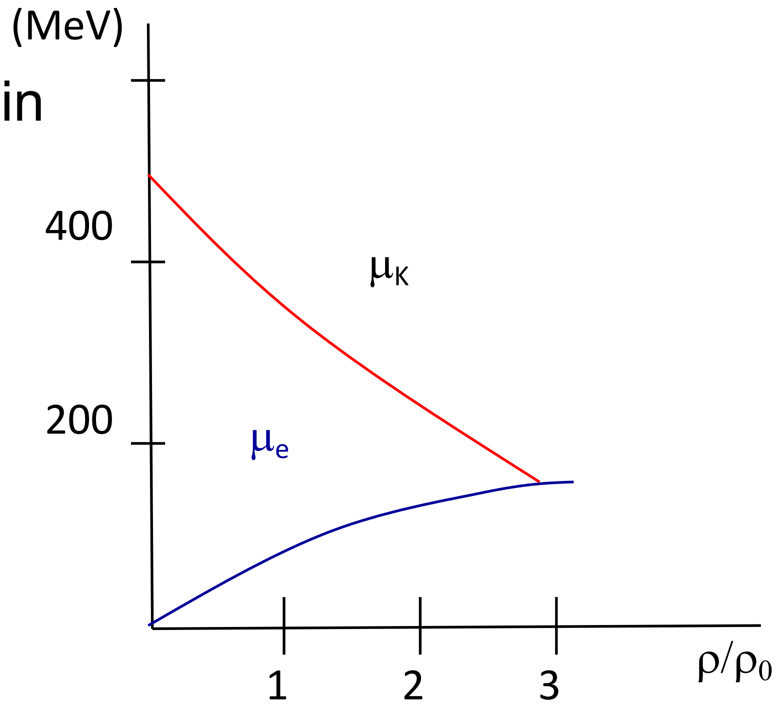
Antikaon potential at saturation density is deeper than -120 MeV

Thapa, Sinha, Li and Sedrakian ‘21



Using microscopic unitarized schemes…

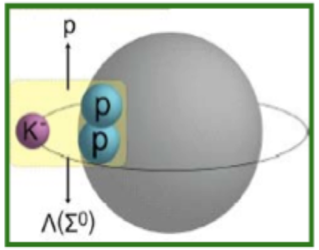
The condition $\mu_{e-} \geq m^*_{K-}$ for a given ρ_c implies that $m_{K-} - m^*_{K-}(\rho_c) \approx 200, 300$ MeV. However, unitarized schemes based on meson-exchange models or chiral Lagrangians predict a moderate attraction in nuclear matter

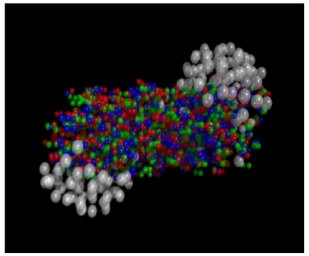


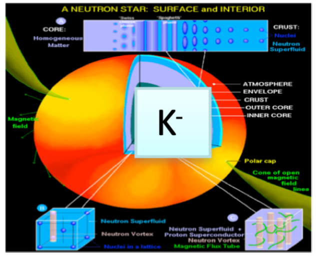
Lutz '98
Ramos and Oset '00
Tolos, Polls, Ramos '01
Tolos, Ramos and Oset '06
Tolos, Cabrera and Ramos '08
Cabrera, Tolos, Aichelin and Bratkovskaya'14

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

THOR
STRONG 2020
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