Strange Mesons in Nuclei and Neutron Stars

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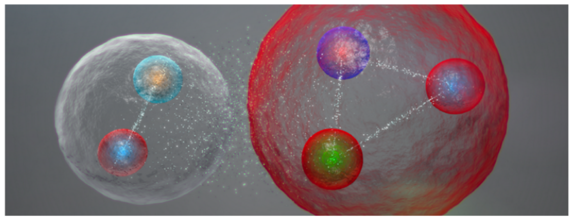
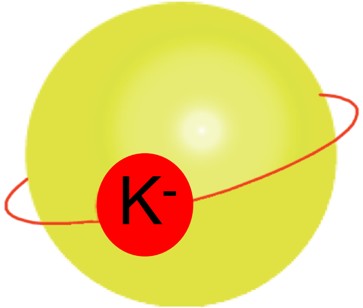
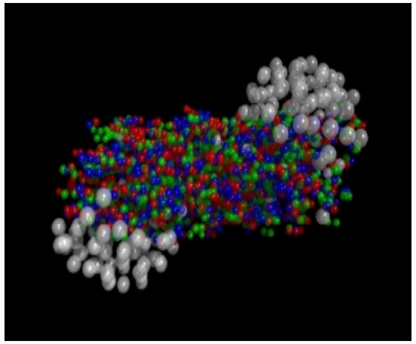
STRANU: HOT TOPICS IN STRANGENESS NUCLEAR AND ATOMIC PHYSICS





Outline

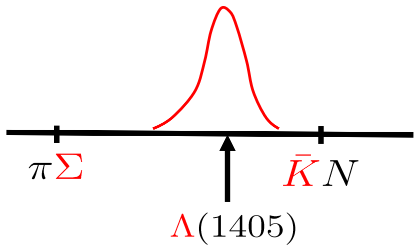


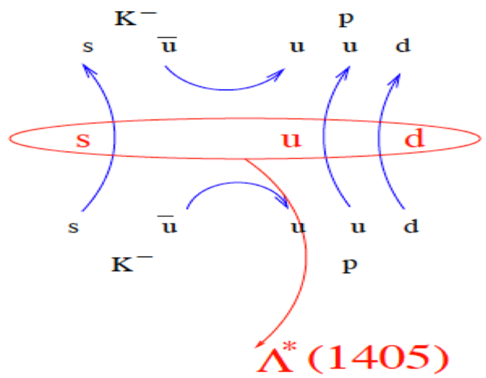
- $\bar{K}N$ interaction: $\Lambda(1405)$ resonance
- $\bar{K}NN$ bound state
- Kaons and Antikaons in matter
- Experiments and observations: from atoms to stars
- Present and Future

$\bar{K}N$ interaction: the $\Lambda(1405)$

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

- $\bar{K}N$ scattering in the I=0 channel is governed by the presence of the $\Lambda(1405)$ 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, Hosaka '12
Feijoo, Magas and Ramos '19….

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

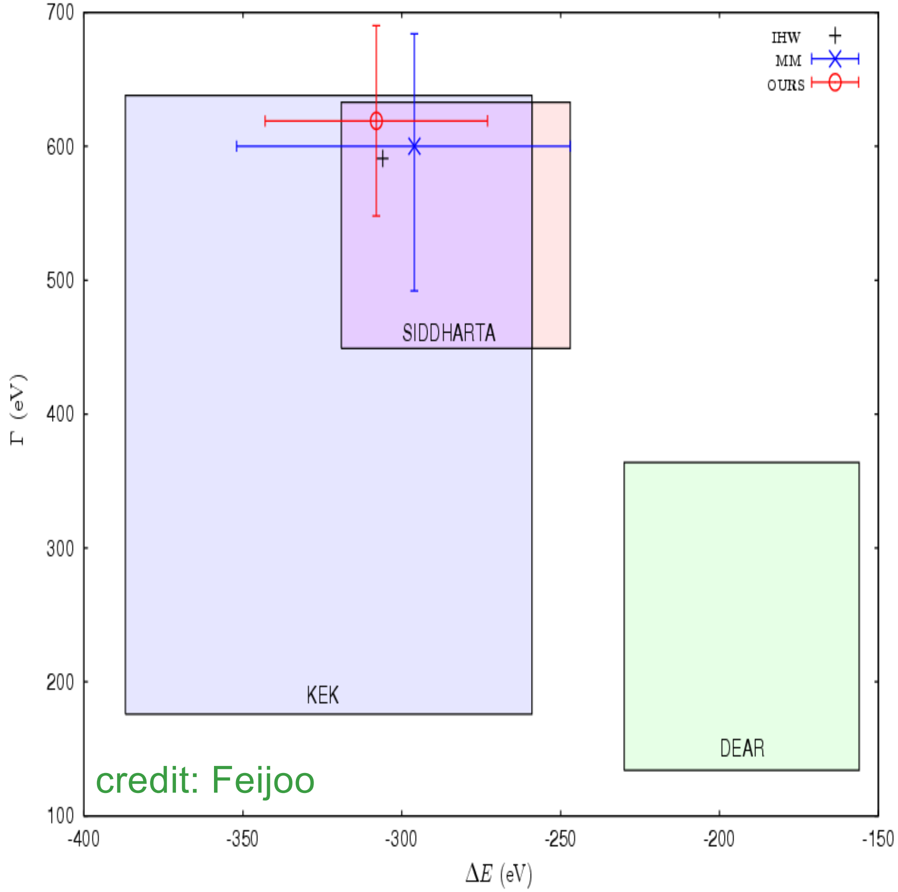
Shift and width of the 1s state of the kaonic hydrogen

The SIDDHARTA collaboration at DAΦNE collider has determined the most precise values of the **shift and width of the 1s state of the kaonic hydrogen**, clarifying the discrepancies between KEK and DEAR results

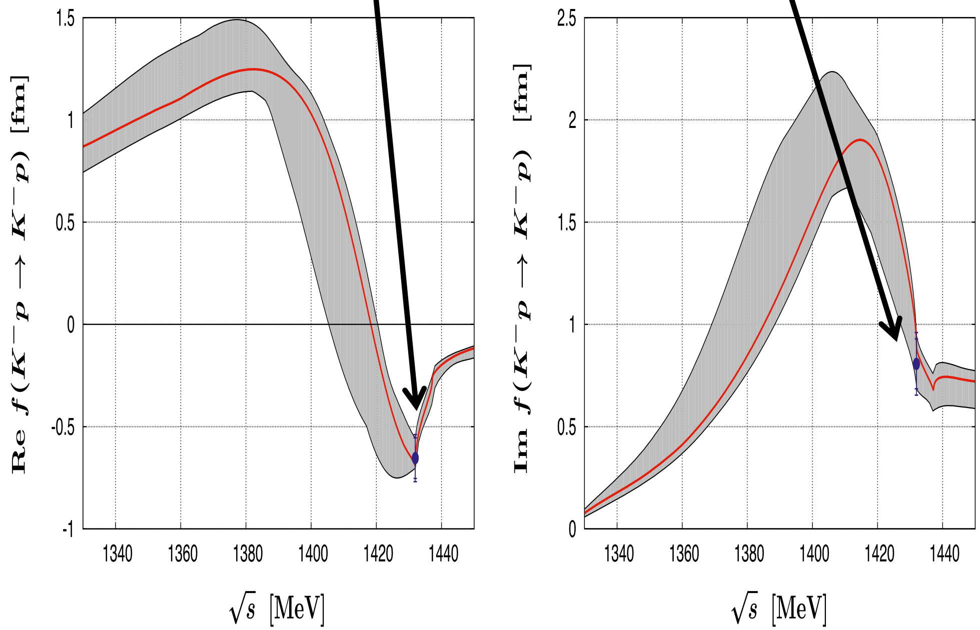
$$\Delta E - i\Gamma/2 = -2\alpha^3\mu_r^2 a(K^-p)[1 + 2\alpha\mu_r(1-\ln\alpha)a(K^-p)]$$

ΔE [eV]	Γ [eV]
$283 \pm 36 \pm 6$	$541 \pm 89 \pm 22$

Bazzi et al. '11



Ikeda, Hyodo and Weise '12



SIDDHARTA results provide important constraints on theoretical descriptions

Ikeda, Hyodo and Weise '12
Guo and Oller '13
Mai and Meissner '13
Feijoo, Magas and Ramos '15

Double-pole structure of Λ(1405)

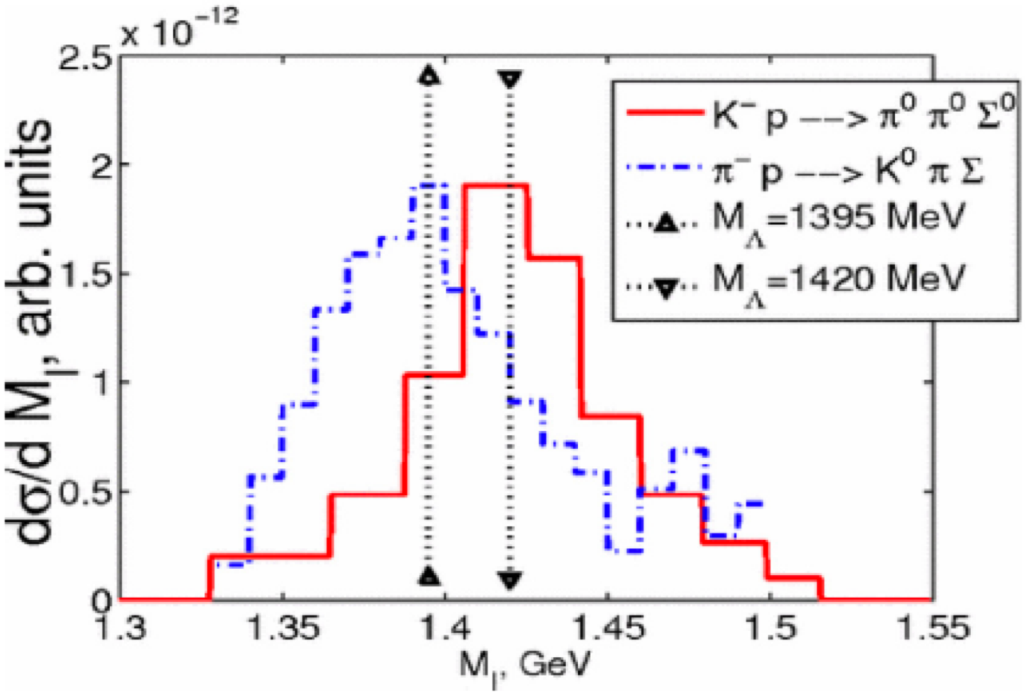
Λ(1405) results from the superposition of two poles in the complex plane, with different coupling to πΣ and $\bar{K}$N states

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

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

PDG

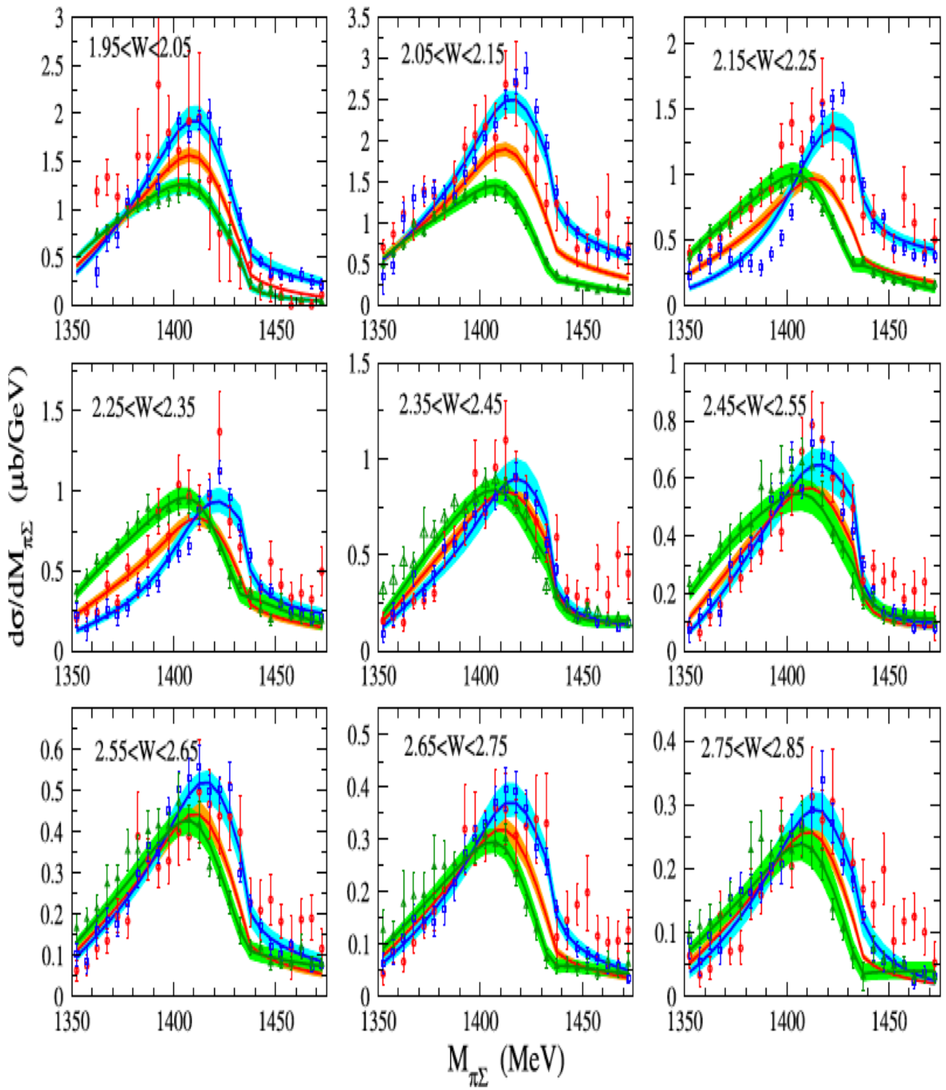
Model		First Pole [MeV]	Second Pole [MeV]
NLO	Ikeda, Hyodo and Weise '12	$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
Fit II	Guo and Oller '13	$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
Solution Nr. 2	Mai and Meissner '15	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$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



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

Λ(1405) production



Σπ invariant mass distributions for different photon energies, where $\pi^0\Sigma^0$ is in red, $\pi^-\Sigma^+$ in blue and $\pi^+\Sigma^-$ in green

Roca and Oset '13

Data from CLAS: Moriya et al '13

Photo-induced reactions

CLAS Moriya et al '13

$$\boxed{\gamma + p \to \Lambda(1405)K^+ \to (\Sigma\pi)^0 K^+}$$

Theory: Nacher et al. '99, Roca and Oset '13, Nakamura and Jido '14, Mai and Meissner '15..

Λ(1405) photoproduction reactions most sensitive to high-energy pole

Kaon-induced reactions sensitive to high-energy pole Magas, Oset and Ramos '05, whereas **Pion-induced reactions** most sensitive to the low-energy pole Hyodo et al. '03

Kaon-induced reactions in deuteron

J-PARC (E31) Naruki et al. '12

$$\boxed{K^- d \to \pi \Sigma n}$$

Theory: Jido, Oset and Sekihara '09 '13, Miyagawa and Haidenbauer '12, Ohnishi et al '16, Miyagawa, Haidenbauer and Kamada '18..

Proton-proton collisions

ANKE Zychor et al '08

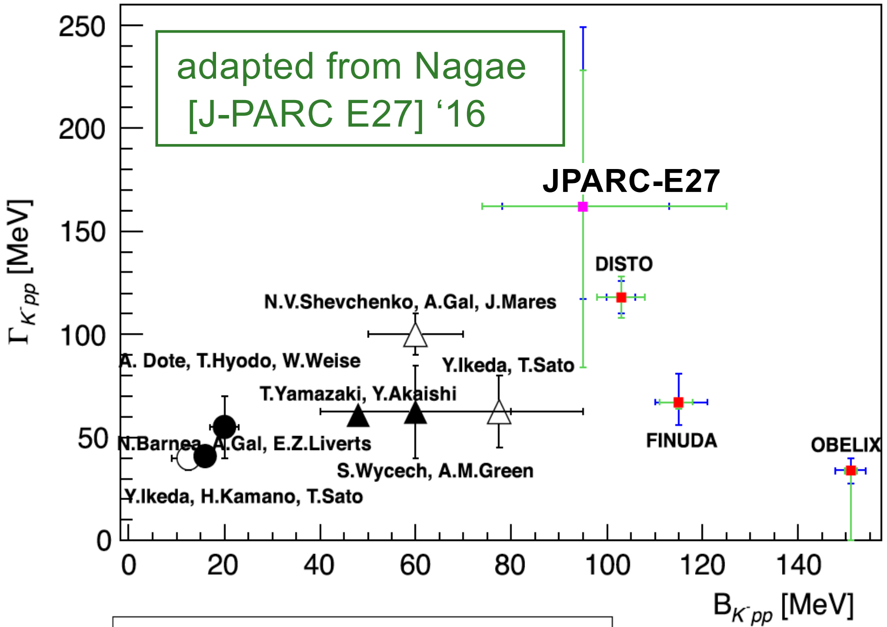
$$\boxed{pp \to pK^+ \Lambda(1405)}$$

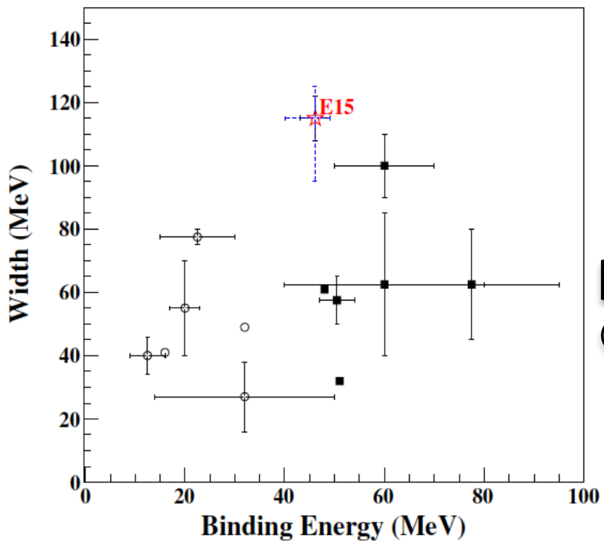
Theory: Geng and Oset '17..

$\bar{K}NN$ 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





Sakuma et al. '20

pheno

chiral

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 alternative 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 has 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

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

Kaons and Antikaons in matter

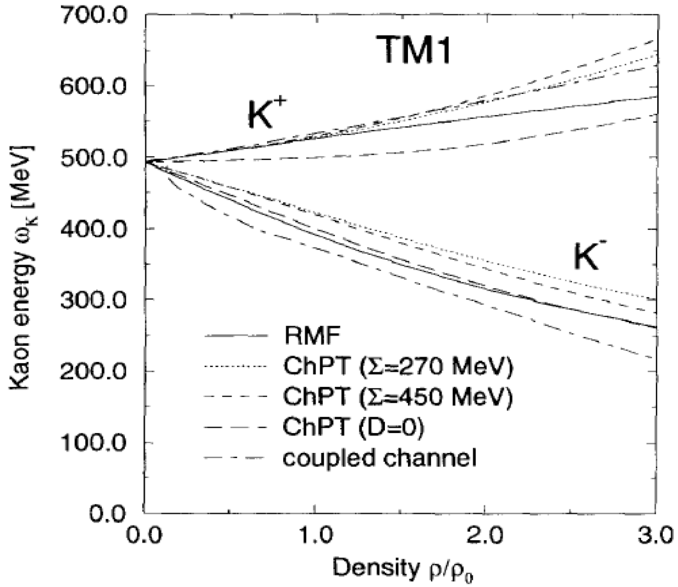
KN interaction in matter

Since no baryonic resonances with positive strangeness exist (assuming no pentaquarks), the KN interaction at low densities can be described by

$$U_K \sim T_{KN-KN}\ \rho,$$

This is the so-called low-density theorem or Tρ approximation
Different models throughout time

Schaffner-Bielich, Mishustin and Bondorf '97



Nambu-Jona-Lasinio (NJL)
10% change in mass at $\rho=\rho_0$ Lutz, Steiner and Weise '94

Relativistic mean-field (RMF)
repulsive potential similar to NJL at ρ_0
Schaffner, Bondor and Mishustin '97

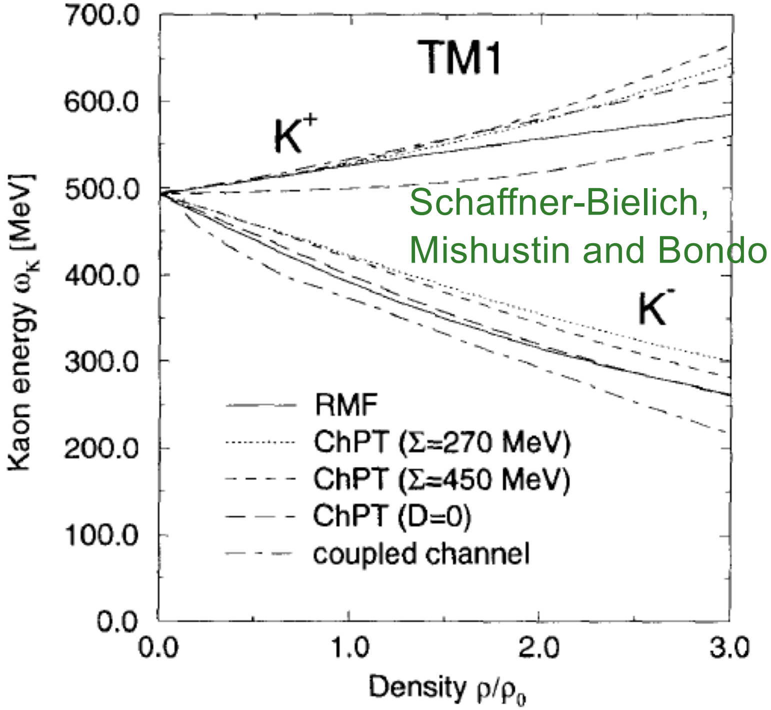
Quark-meson-coupling (QMC)
repulsive potential ~20 MeV at ρ_0 Tsushima et al. '98

Unitarized coupled-channel approaches Oset, Ramos '98; Kaiser, Siegel, Weise '95
with SU(3) chiral Lagrangian: 10% or less change in mass at $\rho=\rho_0$

$\bar{K}N$ interaction in matter

Relativistic mean-field, Quark meson coupling models…

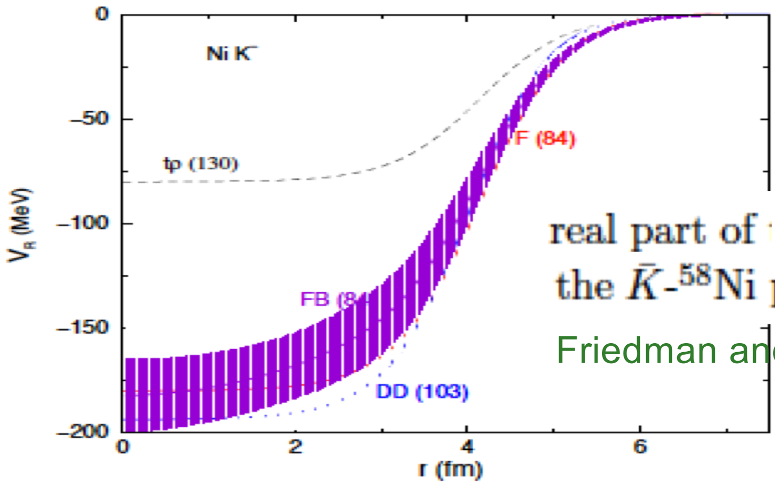
RMF: early works based on meson-exchange picture or the chiral approach for the $\bar{K}N$ interaction on the mean-field level and fit the parameters to the $\bar{K}N$ scattering length



Schaffner-Bielich, Mishustin and Bondorf ‘97

Phenomenological models

density dependent potentials fitted to kaonic atoms



real part of the $\bar{K}$-^{58}Ni potential

Friedman and Gal ‘07

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

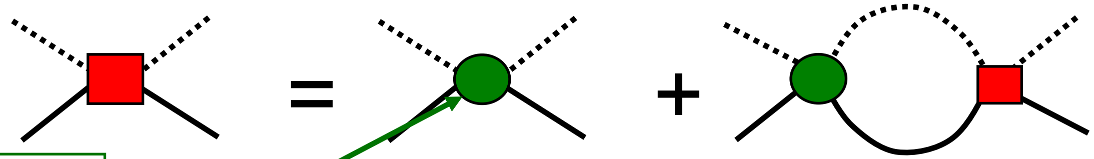
recent K^-N scattering amplitudes from χSU(3) EFT supplemented with phenomenological terms for K^- multinucleon interactions:
kaonic atoms test densities $\rho < \rho_0$

Friedman and Gal ‘17

Unitarized theory in matter:

selfconsistent coupled-channel procedure

Free space

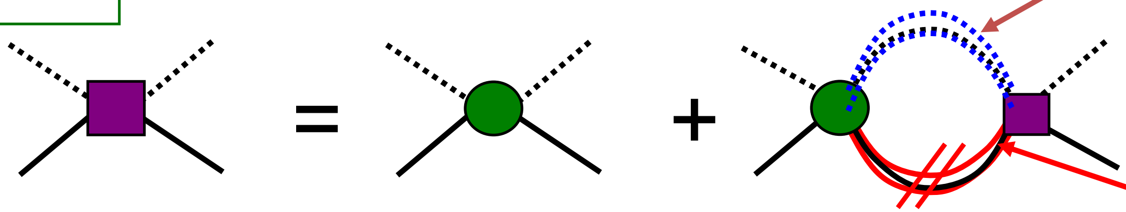


potential from chiral dynamics or meson-exchange models

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

meson dressing

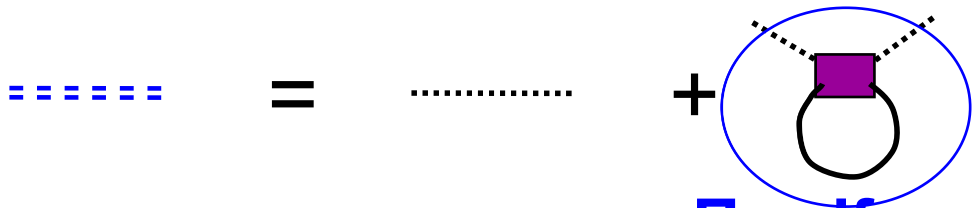
Medium



Pauli blocking and baryon dressing

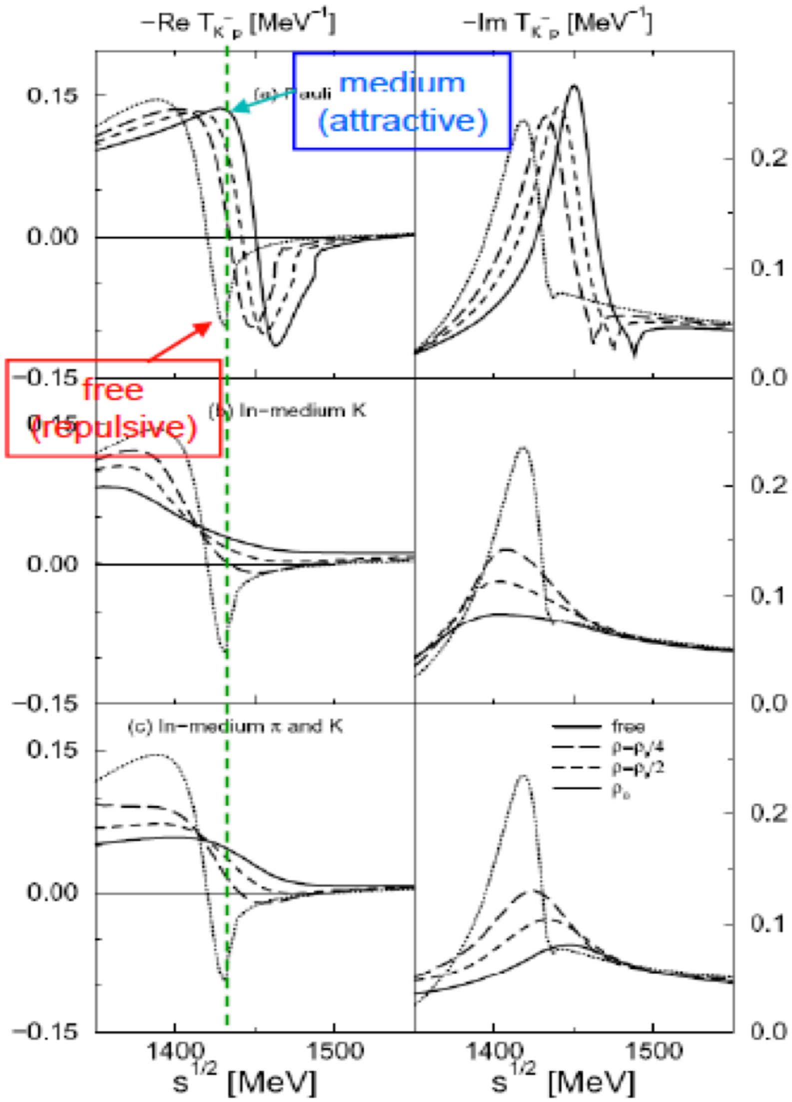
$$T_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, T_{lj}(\rho,T)$$

Dressed meson:

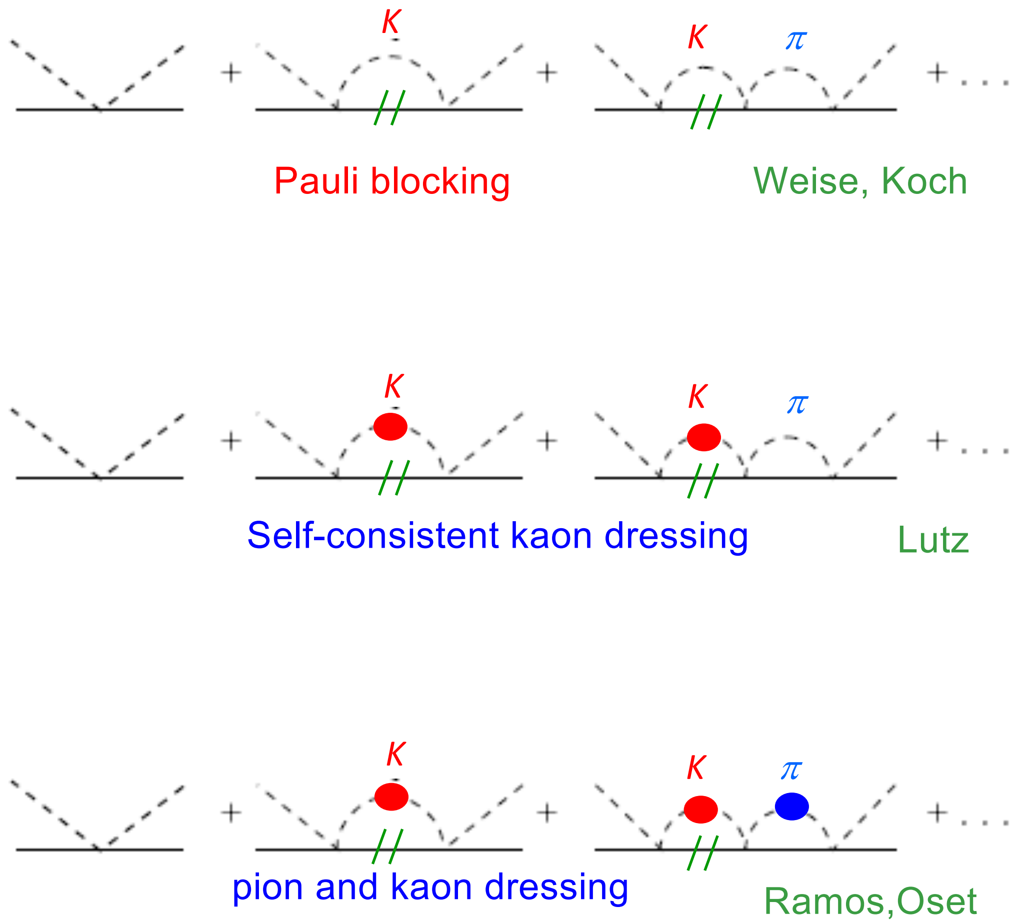


Π self-energy

The presence of the Λ(1405) resonance makes the in-medium $\bar{K}N$ interaction very sensitive to the particular details of the many-body treatment.



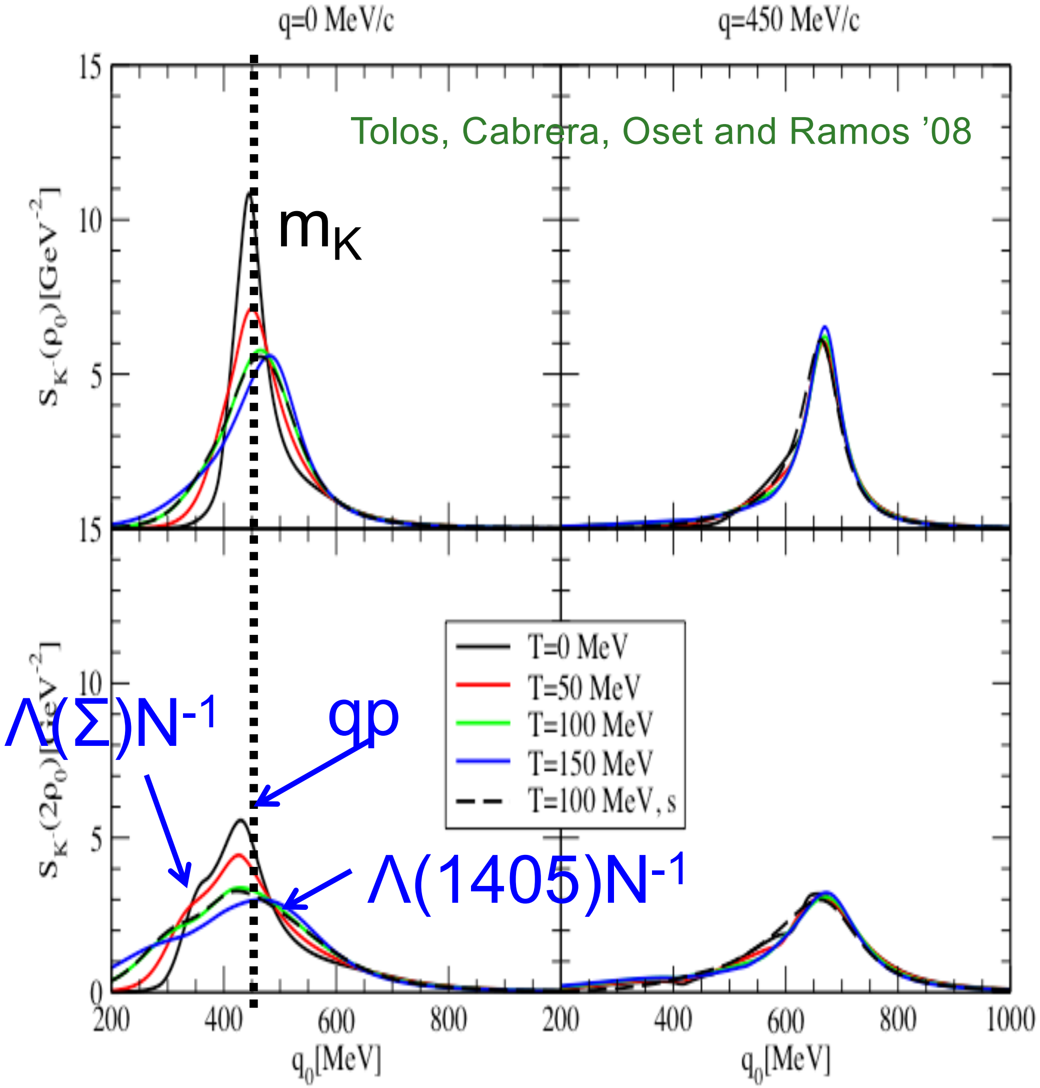
Ramos and Oset '00 (chiral model)



$\bar{K}$ spectral function in matter

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

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…



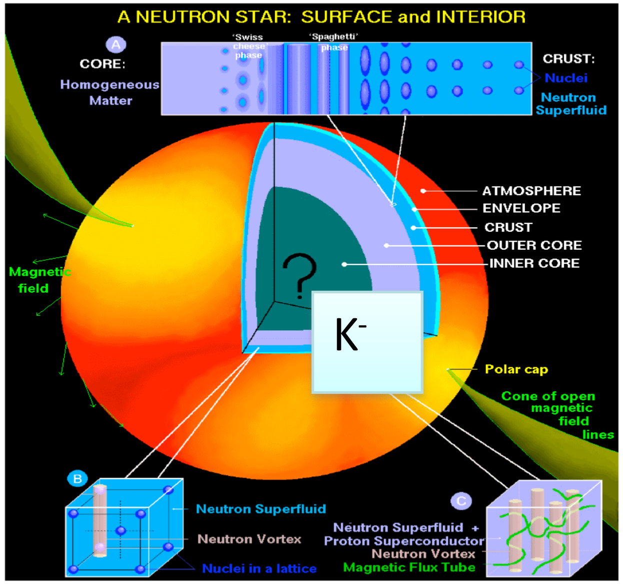
Re $U_{K^-}(\rho_0)$ ~ -50 to -80 MeV

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

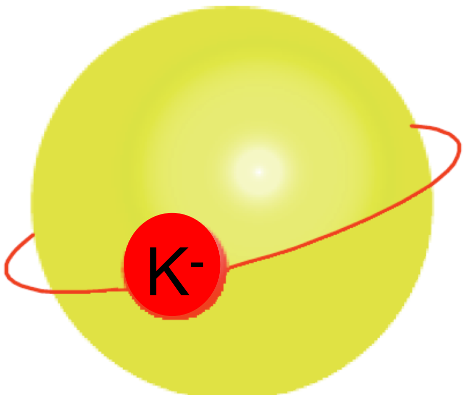
- **s-wave** $\bar{K}N$ interaction governed by $\Lambda(1405)$: attraction due to modified $\Lambda(1405)$ in the medium using a self-consistent coupled-channel approach

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

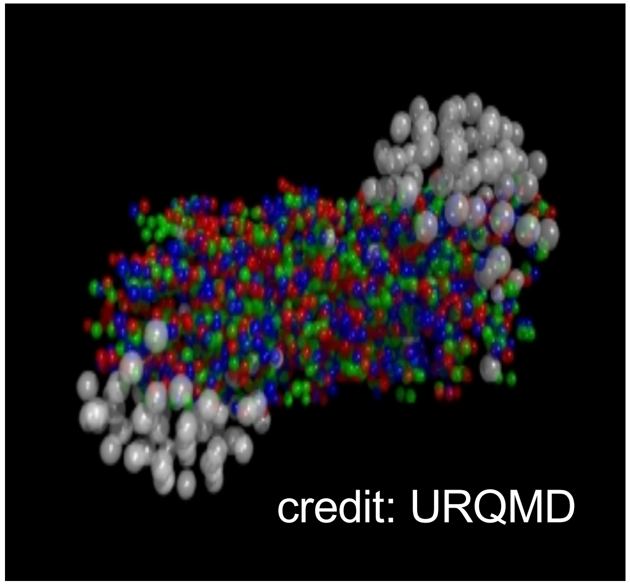
Experiments and observations: from atoms to stars



pioneer work of Kaplan and Nelson ‘86



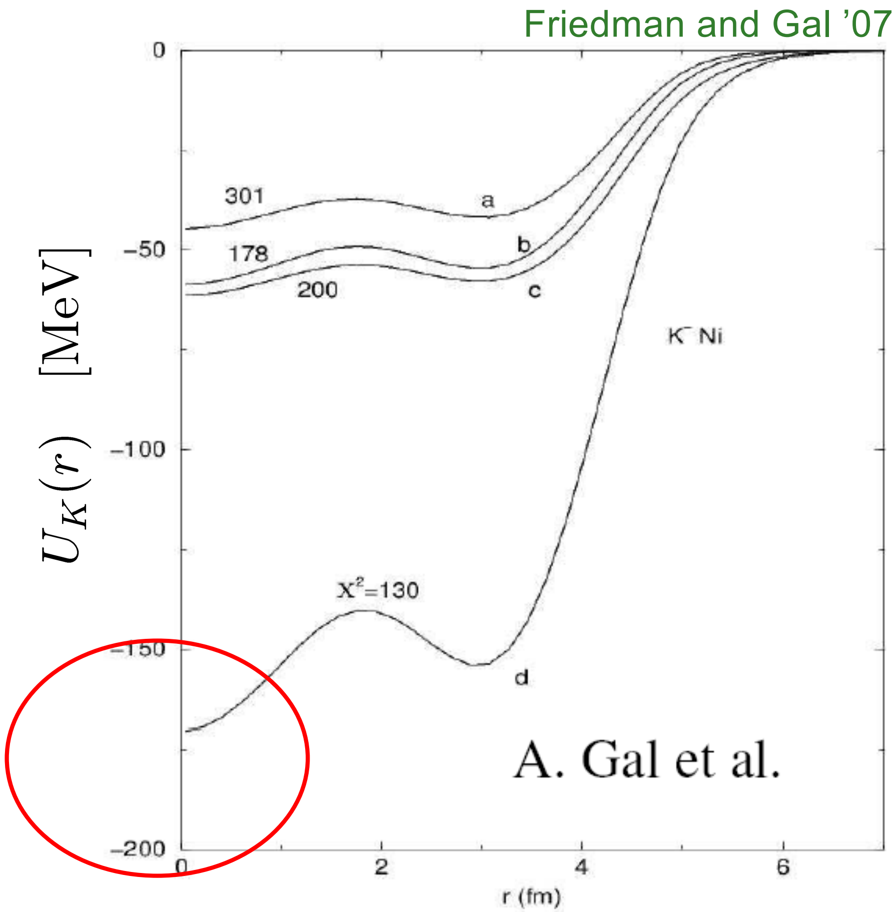
review: Friedman and Gal ’07 ‘17


credit: URQMD

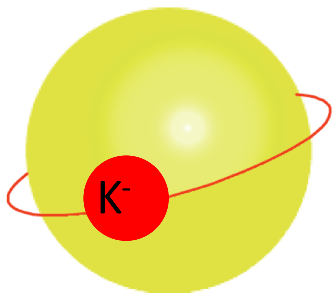
Kaonic atoms

Kaonic atoms are atoms in which an electron is replaced by a negatively charged antikaon

Friedman and Gal '07



$^7Li, ^9Be, ^{12}C, ^{208}Pb$..

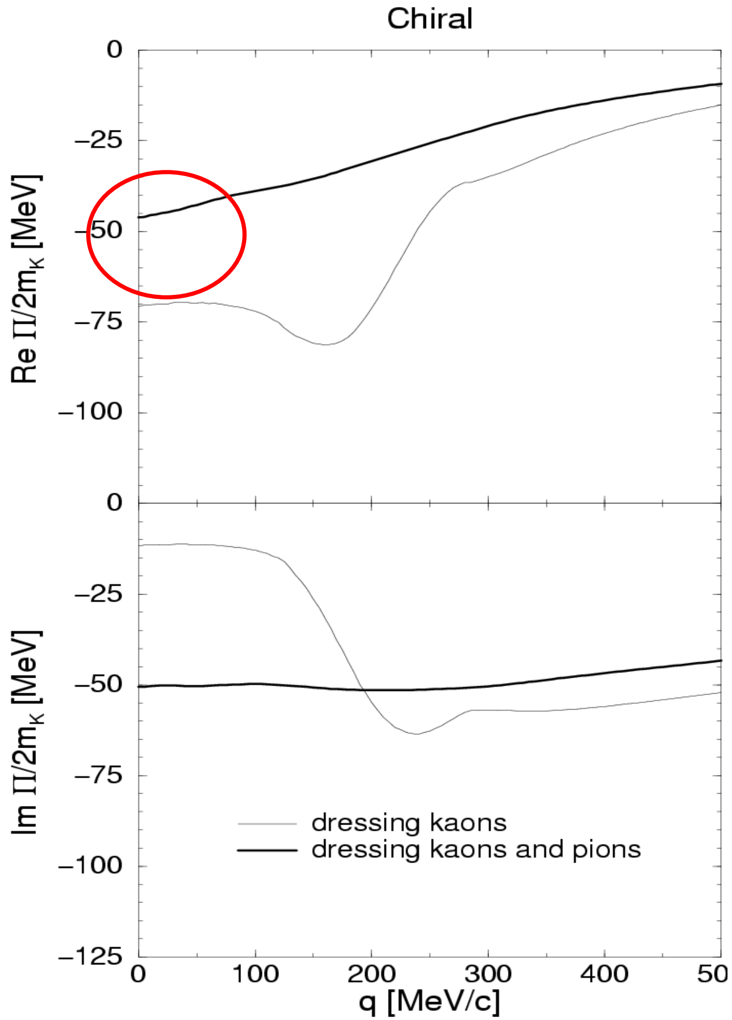


best fits to **kaonic atoms** seem to prefer
$U_K \sim -200$ MeV at ρ_0

$$\left(-\nabla^2 + m_K^2 + 2m_K U_K(r) + V_{\mathrm{Coul.}}\right)\Psi_K(r) = {E_K}^2\,\Psi_K(r)$$

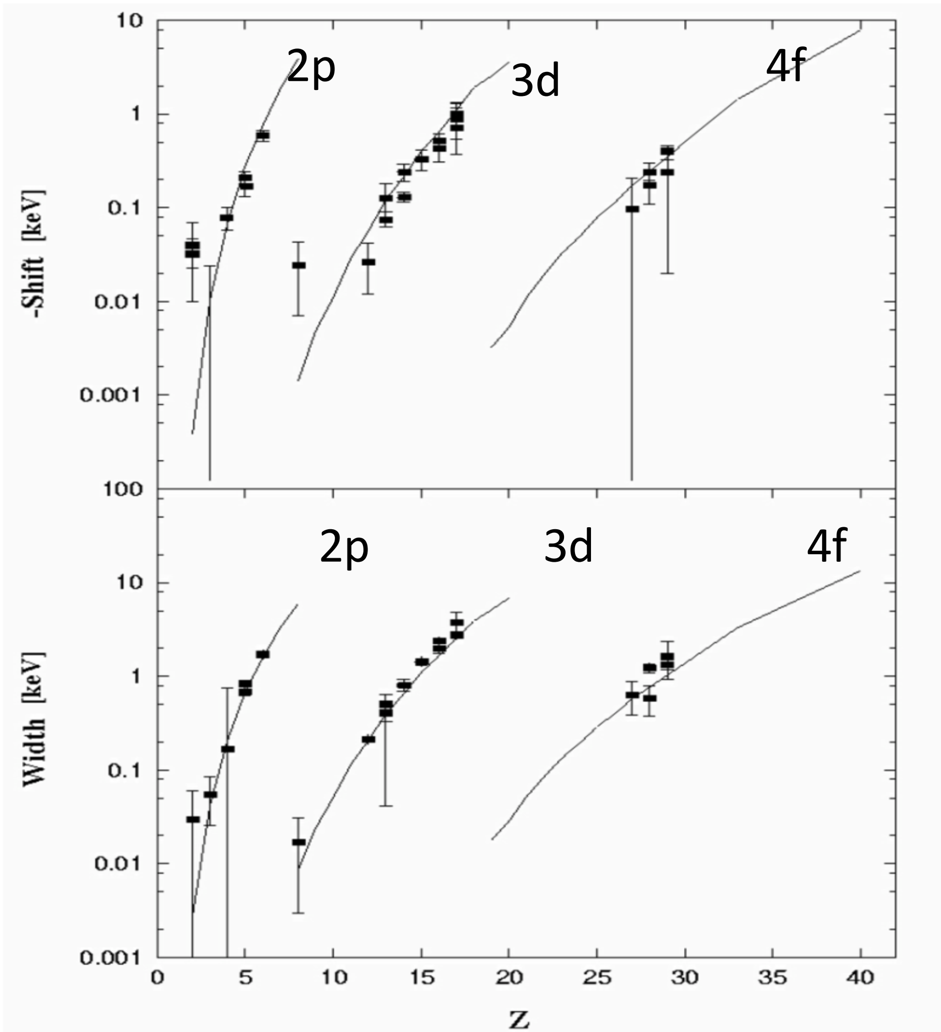
However, theoretical models based on the chiral $\bar{K}N$ interaction with many-body effects (albeit an additional moderate phenomenological piece) → moderate attraction for the K^--nucleus potential and **kaonic atoms** are also well described!!

moderate $\bar{K}N$ interaction:



Ramos and Oset '00 (chiral model)

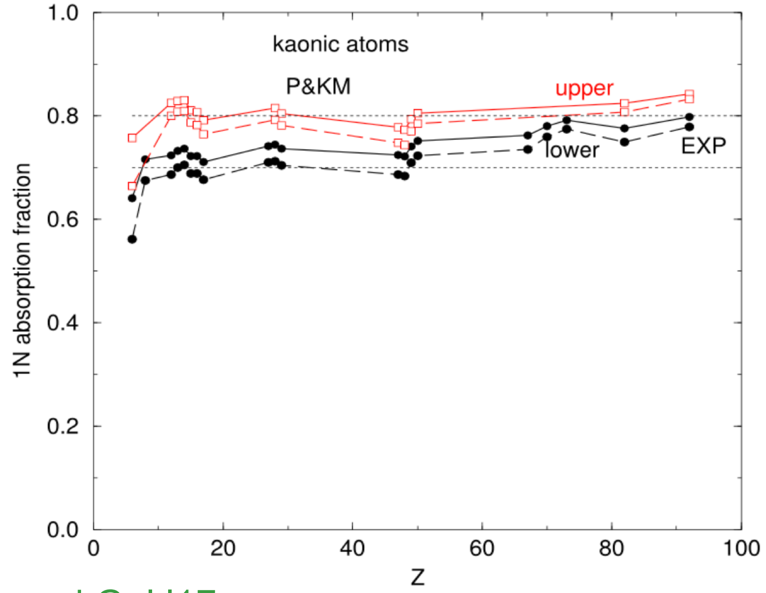
Kaonic atoms



Hirenzaki et al. '00; Baca, García-Recio and Nieves '00

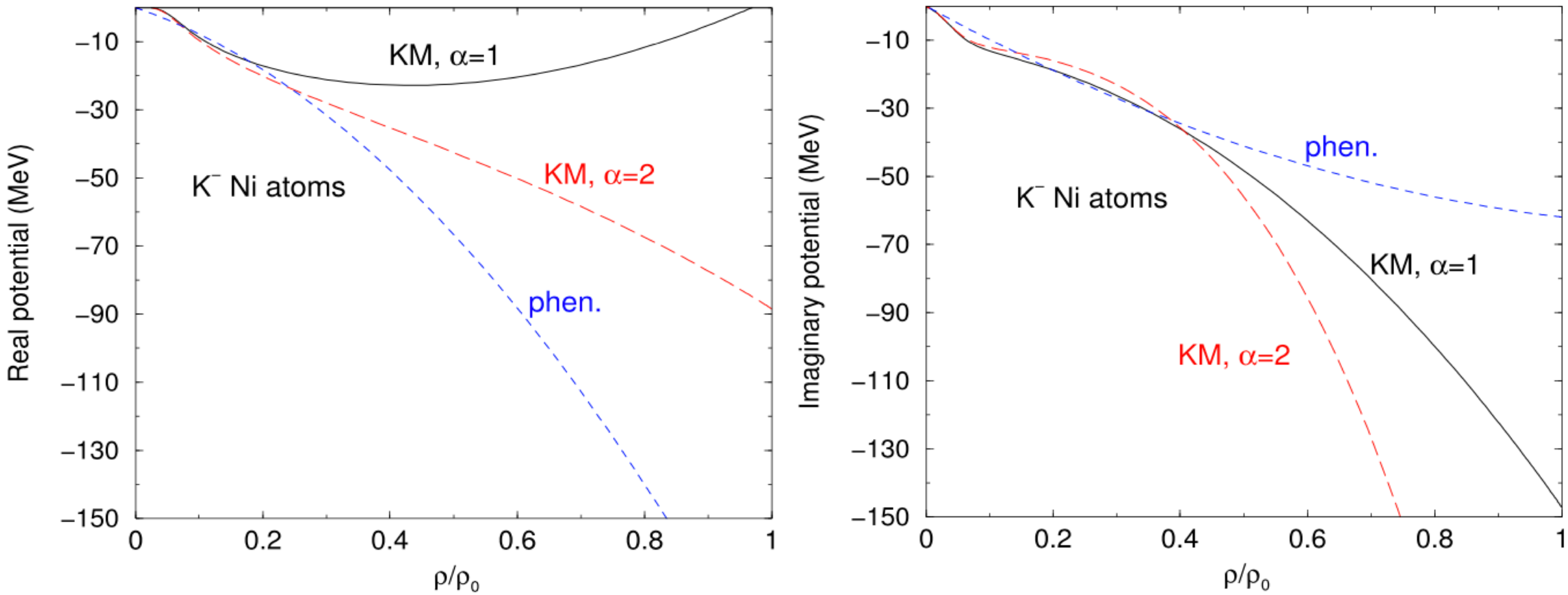
Reanalysis using chirally-motivated meson-baryon coupled-channel models supplemented with phenomenological term representing K^- multi-nucleon interactions

Friedman and Gal ’17: Hrtankova and Mares ‘17



agreement of the calculations with the estimated single-nucleon absorption fractions

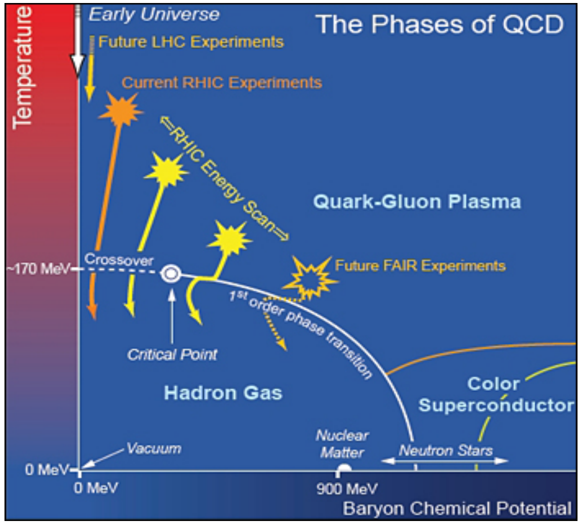
Friedman and Gal ’17



kaonic data only constrains the K^- optical potential for $\rho < 25\% \ (50\%) \ \rho_0$

Strangeness production in 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^+, $K^*(892)^0$, $\phi(1020)$, $\Xi(1321)$,Ω,...

Zinyuk (FOPI) '14
Foerster et al (KaoS) '07
Agakishiev et al (HADES) '13 '14
Galatyuk (HADES) '17..

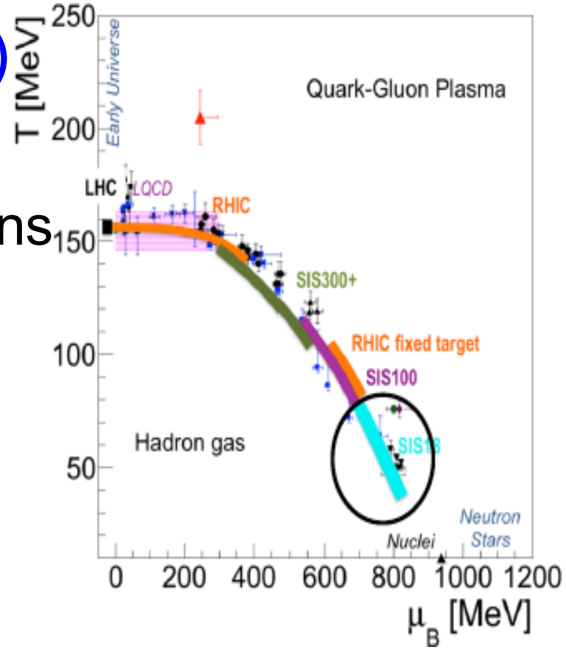
high-energy HICs:
STAR/RHIC: $K^*(892)^0$, $\phi(1020)$, Ω..
ALICE/LHC: $K^*(892)^0$, $\phi(1020)$, $\Sigma^{+-}(1385)$, $\Xi(1530)^0$..

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 $\phi \rightarrow K^+ K^-$?

New 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,...

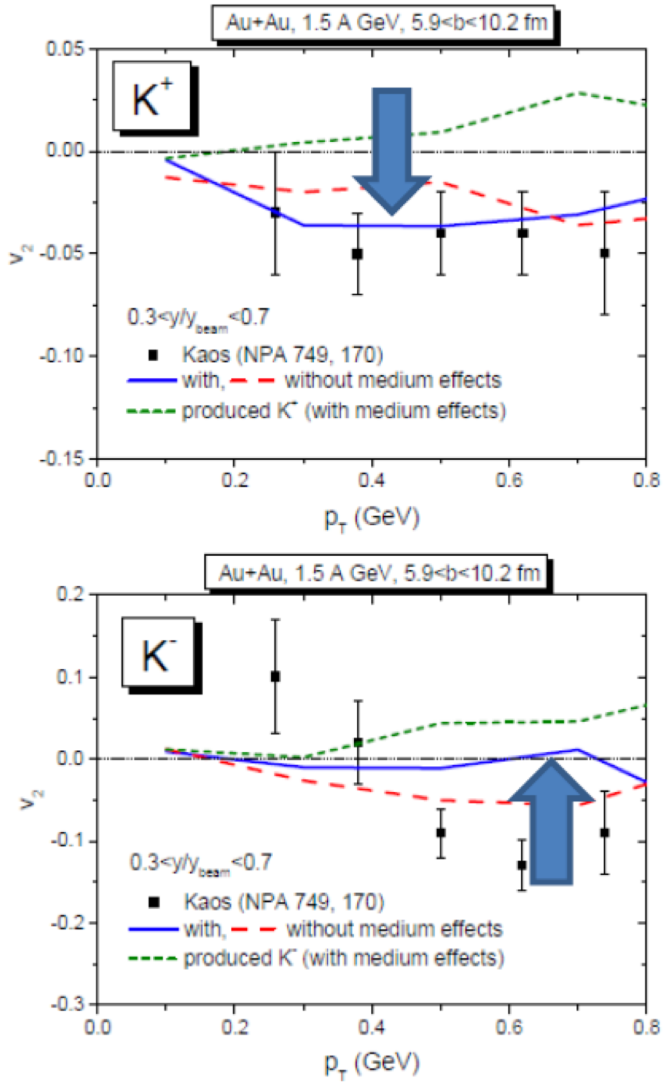
- K^+ in-medium potential is repulsive: $U_{KN}(\rho_0) \approx 20...40$ MeV
- K^- from Φ decay wash out the effects of the potential (spectra and flow!!)

- 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

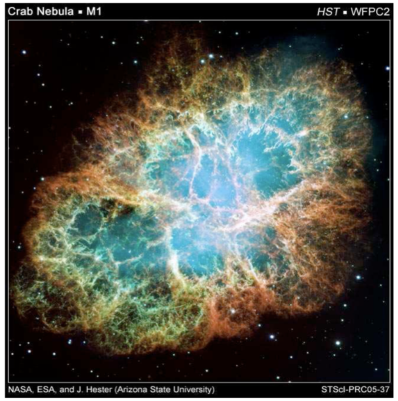
- The nuclear effects on (anti)kaon are more prominent in the collision of large nuclei
- (Anti)kaon production is (enhanced)suppressed due to (broadening of spectral function)repulsive kaon potential
- (Anti)kaon spectrum becomes (softer)harder in nuclear matter, whereas y-distribution (shrinks)broadens
- 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

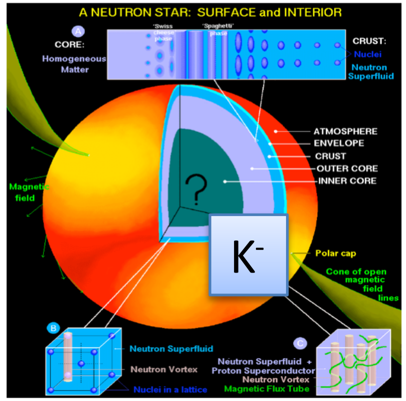


Song et al '21

Kaon condensation in neutron stars

Kaplan and Nelson ‘86
Brown and Bethe ‘94



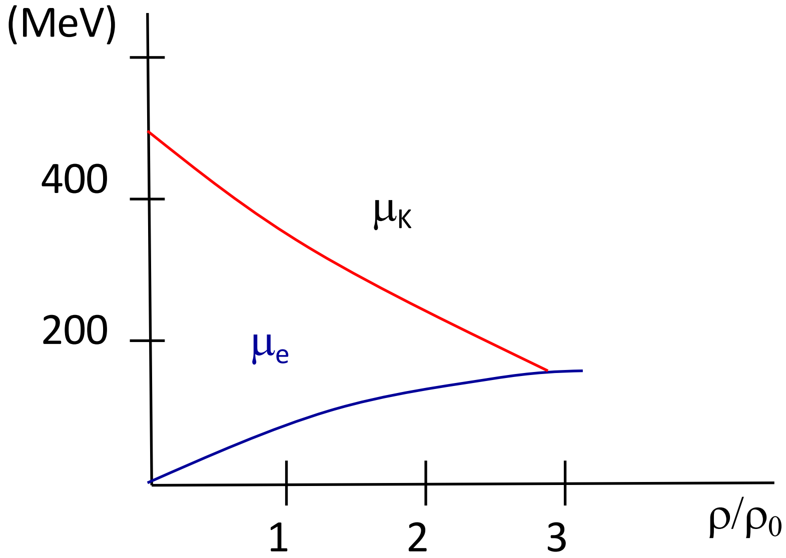


K^- feels attraction in the medium
→ Kaon condensation in neutron stars?

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

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

Kaons are bosons. If $\mu_{e^-} \geq m^*_{K^-}$ for $\rho \geq \rho_c$, with ρ_c being a feasible density within neutron stars, kaons will condensate

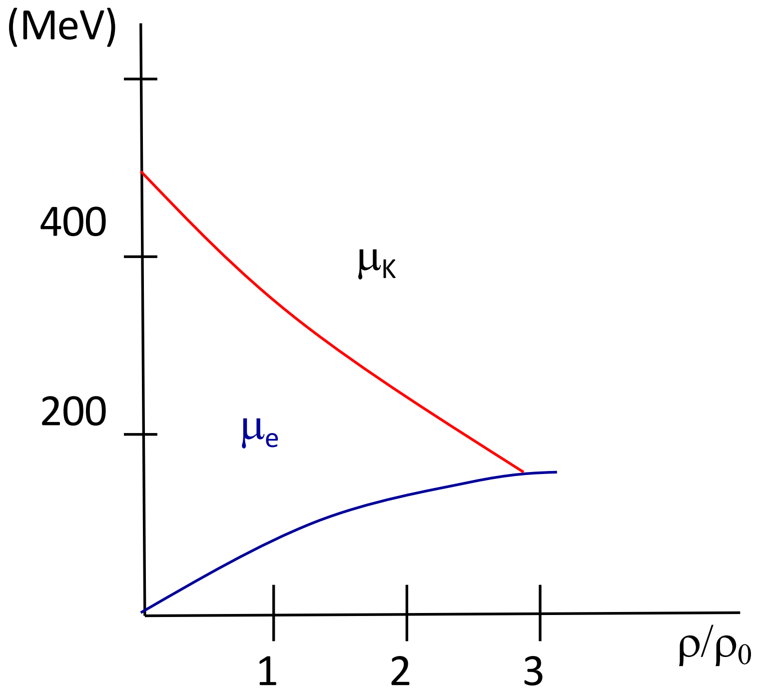


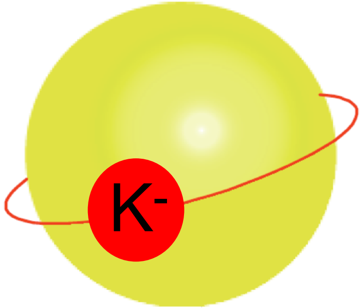
Kaon condensation?

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

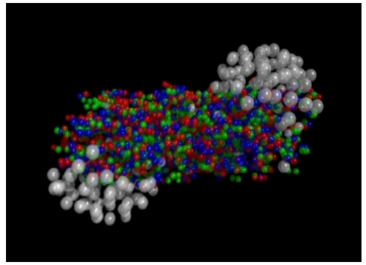
Lutz '98
Ramos and Oset '00
Tolos, Polls, Ramos '01
Tolos, Ramos and Oset '06
Tolos, Cabrera and Ramos '08
Cabrera, Tolos, Aichelin and Bratkovskaya'14

Therefore,
kaon condensation seems very unlikely within unitarized schemes





Present and Future



A lot of experimental and theoretical effort has been invested to understand the antikaon-nucleon interaction, that is governed by the presence of the Λ(1405)

The interest has been focused in unveiling the nature of Λ(1405), and the consequences for the formation of $\bar{K}NN$ bound states

Kaons and antikaons in matter have been also investigated, in connection to kaonic atoms, creation and propagation of kaons/antikaons in nuclear collisions and kaon condensation in neutron stars

STRONG 2020
THOR
PHAROS THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS
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