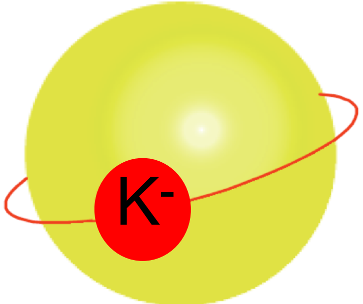
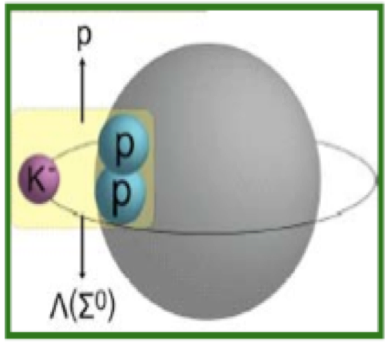
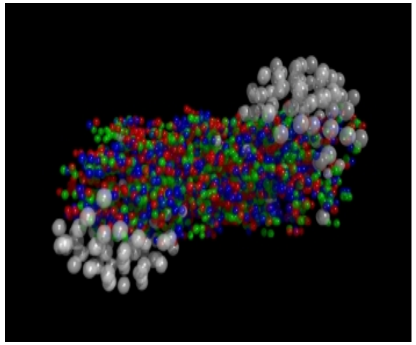
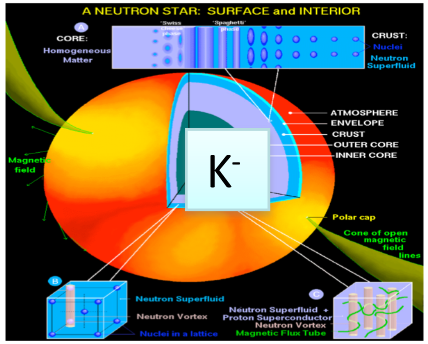








Strange mesons in nuclei and neutron stars

FIAS Frankfurt Institute for Advanced Studies

Laura Tolós

Institute of Space Sciences

CSIC
Consejo Superior de Investigaciones Científicas

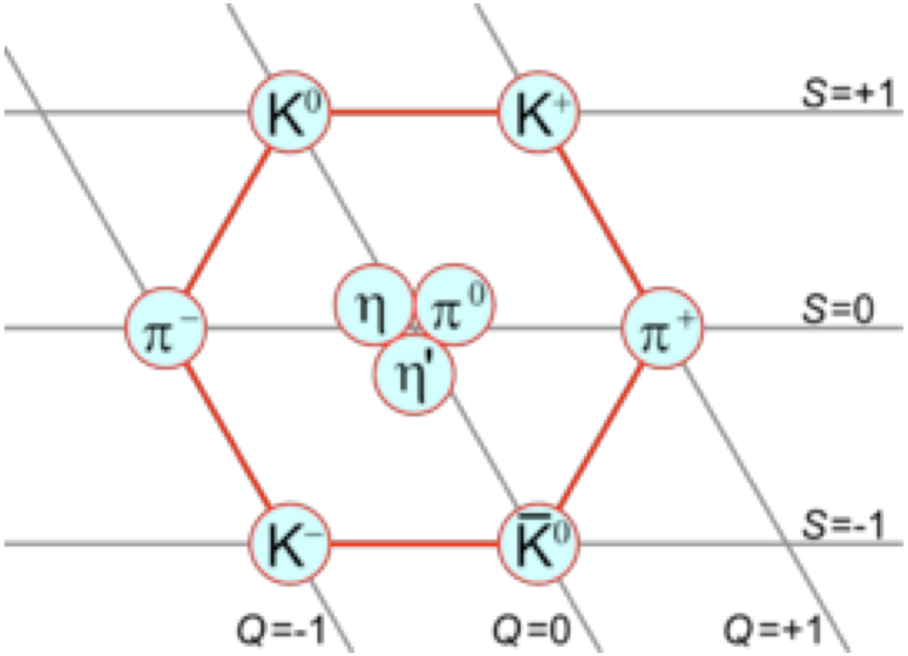
IEEC

FNHP2022
FRONTIERS IN NUCLEAR AND HADRONIC PHYSICS
School at the Galileo Galilei Institute for Theoretical Physics
Florence, February 21 - March 04, 2022

Strange mesons: $\bar{K}$ and K

An (anti-)kaon is a meson containing one (strange)anti-strange quark

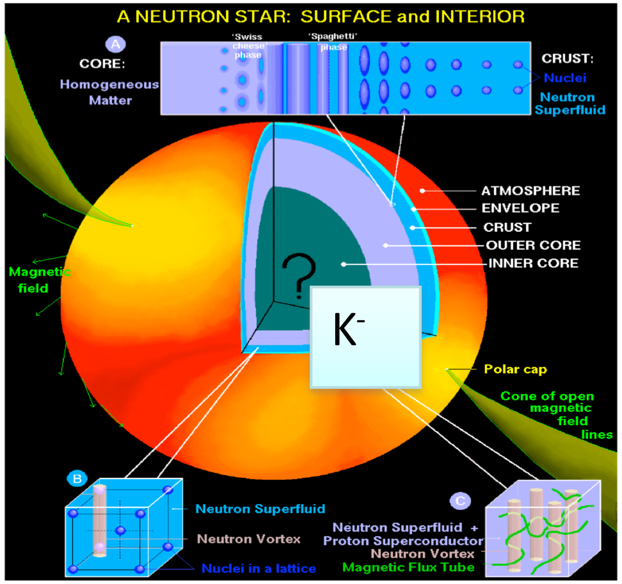
Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

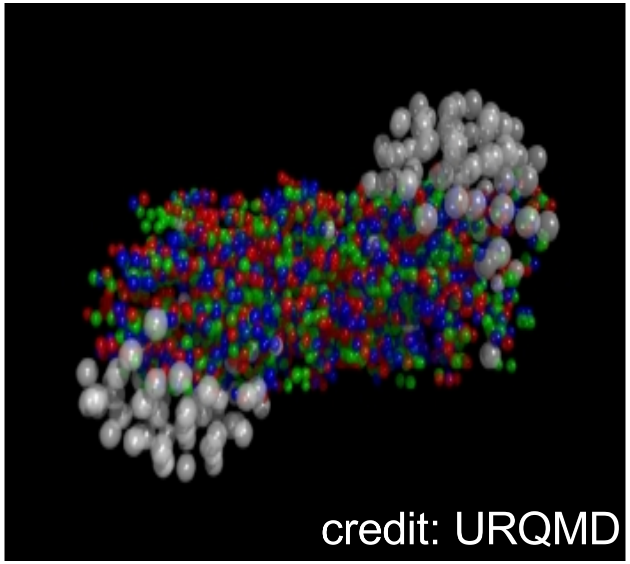


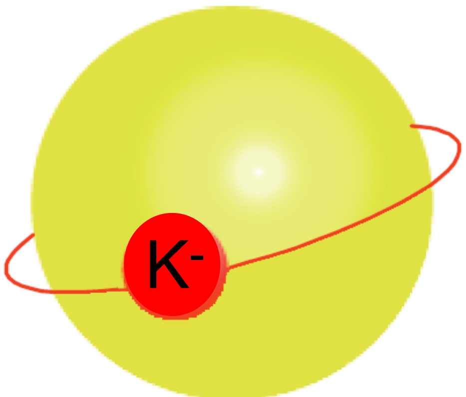
$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \quad \begin{matrix} u\bar{s} \\ d\bar{s} \end{matrix} \qquad s = 1$$

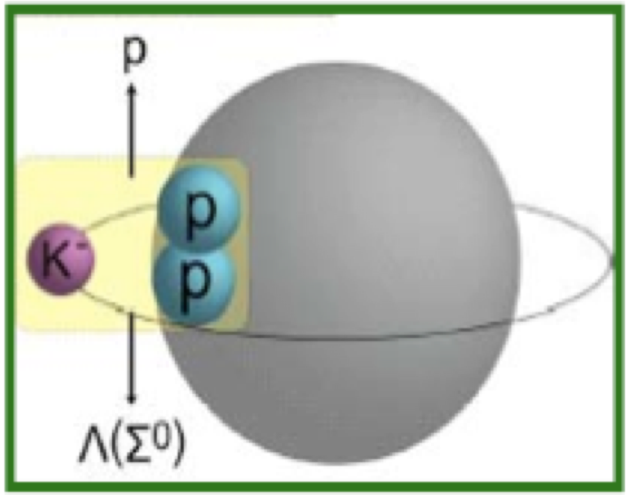
$$\bar{K} = \begin{pmatrix} \bar{K}^0 \\ -K^- \end{pmatrix} \quad \begin{matrix} \bar{d}s \\ \bar{u}s \end{matrix} \qquad s = -1$$

Where to find strange mesons?









FINUDA, DISTO, OBELIX, J-PARC..

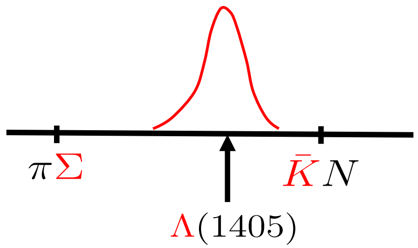
Outline

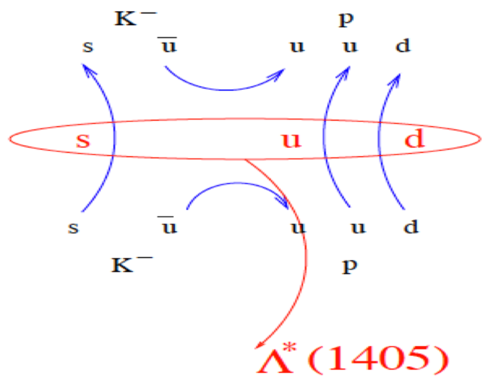
- $\bar{K}N$ interaction: $\Lambda(1405)$ resonance
- $\bar{K}NN$ bound state
- Kaons and Antikaons in matter
- Experiments and observations: from atoms to stars
- Bibliography

$\bar{K}N$ 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

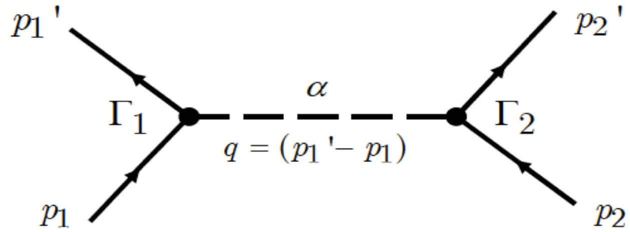
Kaiser, Siegl and Weise, '95; Oset and Ramos '98;
Oller and Meissner '01; Lutz, and Kolomeitsev '02;
Garcia-Recio et al. '03; Jido et al. '03; Borasoy, Nissler, and Weise '05;
Oller, Prades, and Verbeni '05; Oller '06;
Borasoy, Nissler and Weise '05;
Khemchandani, Martinez-Torres, Nagahiro, Hosaka '12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

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

$\bar{K}N$ interaction:
meson-exchange model

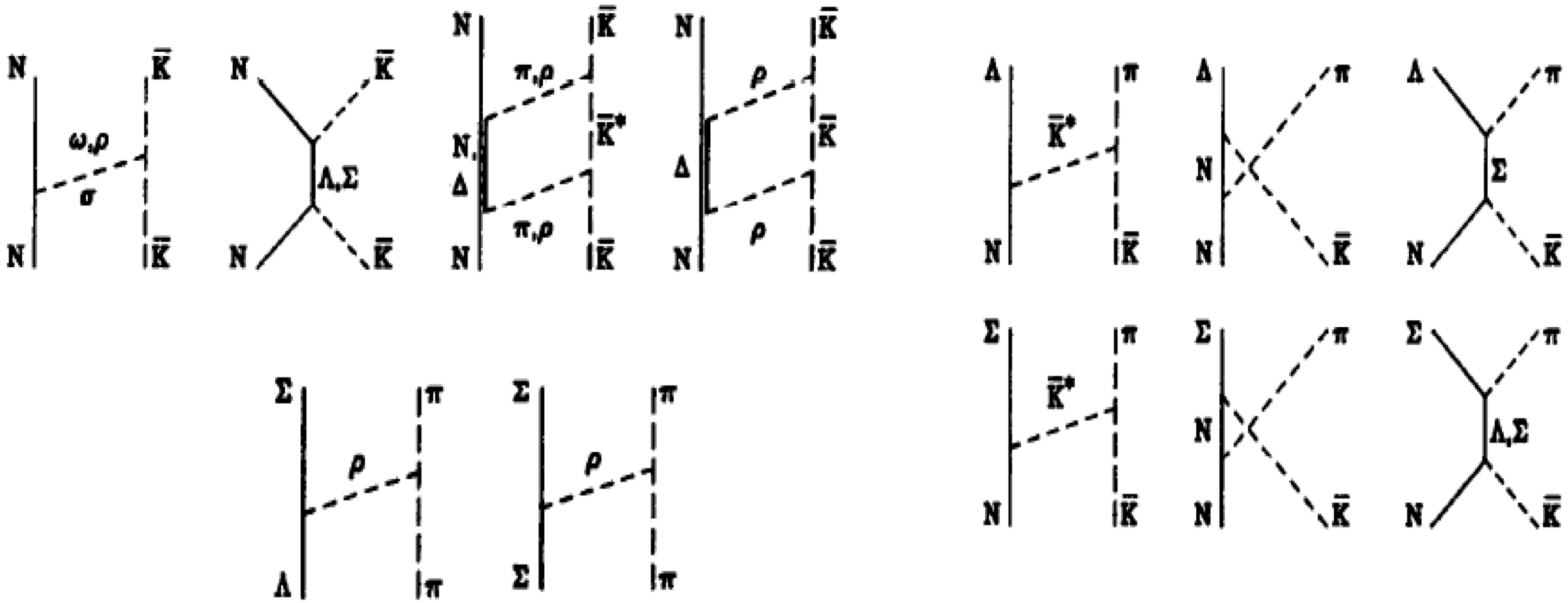
Mueller-Groeling, Holinde and Speth '90; Buettgen, Holinde, Mueller-Groeling, Speth and Wyborny '90; Hoffmann, Durso, Holinde, Pearce and Speth '95; Haidenbauer, Krein, Meissner and Tolos '11..

The One Boson Exchange model
to consider the exchange of bosons between baryon-baryon (or meson-baryon or meson-meson) within quantum field theory in terms of perturbation theory using Feynman diagrams



Juelich meson-exchange model

Mueller-Groeling, Holinde and Speth '90



$\bar{K}N$ interaction: SU(3) chiral Lagrangian

$$\phi = (\pi, K, \eta)$$
$$B = (N, \Lambda, \Sigma, \Xi)$$

$$\mathcal{L}^{eff}_{\phi B} = \mathcal{L}^{(1)}_{\phi B} + \mathcal{L}^{(2)}_{\phi B} \,,$$

LO order

$$\mathcal{L}^{(1)}_{\phi B} = i\langle \bar{B}\gamma_\mu [D^\mu, B]\rangle - M_0\langle \bar{B}B\rangle - \frac{1}{2}D\langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle - \frac{1}{2}F\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle \,,$$

NLO order

$$\mathcal{L}^{(2)}_{\phi B} = b_D\langle \bar{B}\{\chi_+, B\}\rangle + b_F\langle \bar{B}[\chi_+, B]\rangle + b_0\langle \bar{B}B\rangle\langle \chi_+\rangle + d_1\langle \bar{B}\{u_\mu, [u^\mu, B]\}\rangle + d_2\langle \bar{B}[u_\mu, [u^\mu, B]]\rangle + d_3\langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle \,.$$

$[D_\mu, B] = \partial_\mu B + [\Gamma_\mu, B]$

$\Gamma_\mu = \frac{1}{2}[u^\dagger, \partial_\mu u]$

$u_\mu = iu^\dagger \partial_\mu U u^\dagger$

$U(\phi) = u^2(\phi) = \exp\left(\sqrt{2}i\phi/f\right)$

f weak decay constant

$g_A = D + F = 1.26$

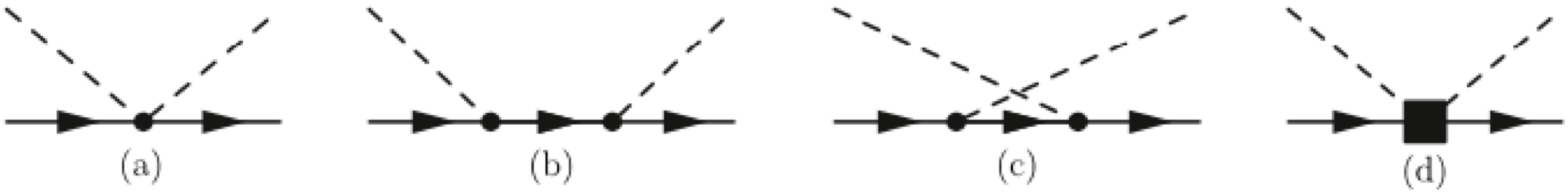
M_0 common baryon octet mass

$\chi_+ = 2B_0(u^\dagger \mathcal{M} u^\dagger + u\mathcal{M}u)$

$\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s)$

$B_0 = -\langle 0|\bar{q}q|0\rangle/f^2$

b_D, b_F, b_0 and d_i $(i = 1, \ldots, 4)$ NLO low-energy constants



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$$\mathcal{L}^{(1)}_{\phi B} = i\langle \bar{B}\gamma_\mu [D^\mu, B]\rangle - M_0\langle \bar{B}B\rangle + \frac{1}{2}D\langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle + \frac{1}{2}F\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle \,,$$

NLO order

$$\mathcal{L}^{(2)}_{\phi B} = b_D\langle \bar{B}\{\chi_+, B\}\rangle + b_F\langle \bar{B}[\chi_+, B]\rangle + b_0\langle \bar{B}B\rangle\langle\chi_+\rangle + d_1\langle \bar{B}\{u_\mu, [u^\mu, B]\}\rangle + d_2\langle \bar{B}[u_\mu, [u^\mu, B]]\rangle + d_3\langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle \,.$$

$$[D_\mu, B] = \partial_\mu B + [\Gamma_\mu, B]$$
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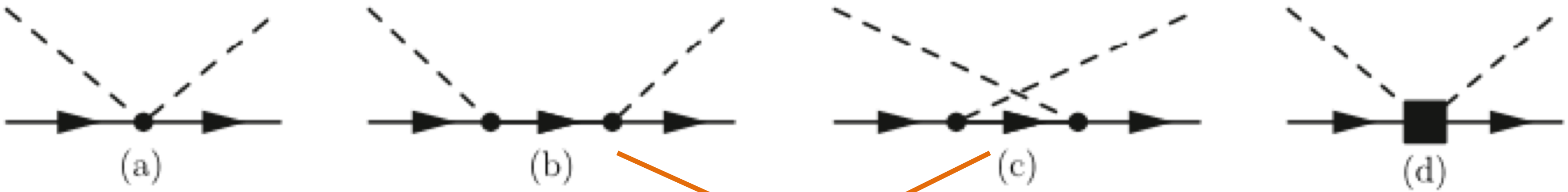
$$B_0 = -\langle 0|\bar{q}q|0\rangle/f^2$$

b_D, b_F, b_0 and d_i $(i = 1, \ldots, 4)$ NLO low-energy constants



Weinberg-Tomozawa interaction (WT)

direct and crossed Born contributions

NLO terms

WT most important contribution, Born terms and NLO contribution needed for fine tuning

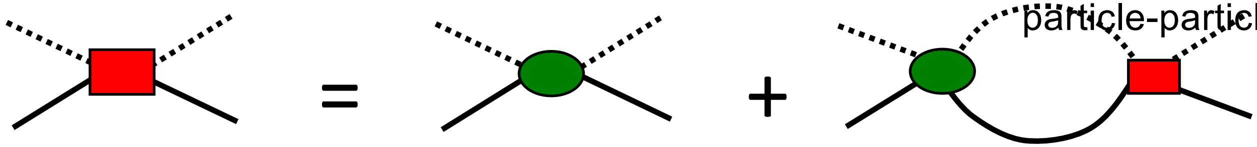
Fine tuning crucial for description of shift and width of the 1s state kaonic hydrogen

Unitarization in coupled channels

S-matrix (collision operator)

final state after collision $|f> = S\,|i>$ initial state

S-matrix $$S_{if} = \delta_{if} - i(2\pi)^4\delta^4(P_i - P_f)T_{if}$$ scattering amplitude



$$T_{if} = V_{if} + V_{il}\, G_l\, T_{lf}$$

model

Cross section

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

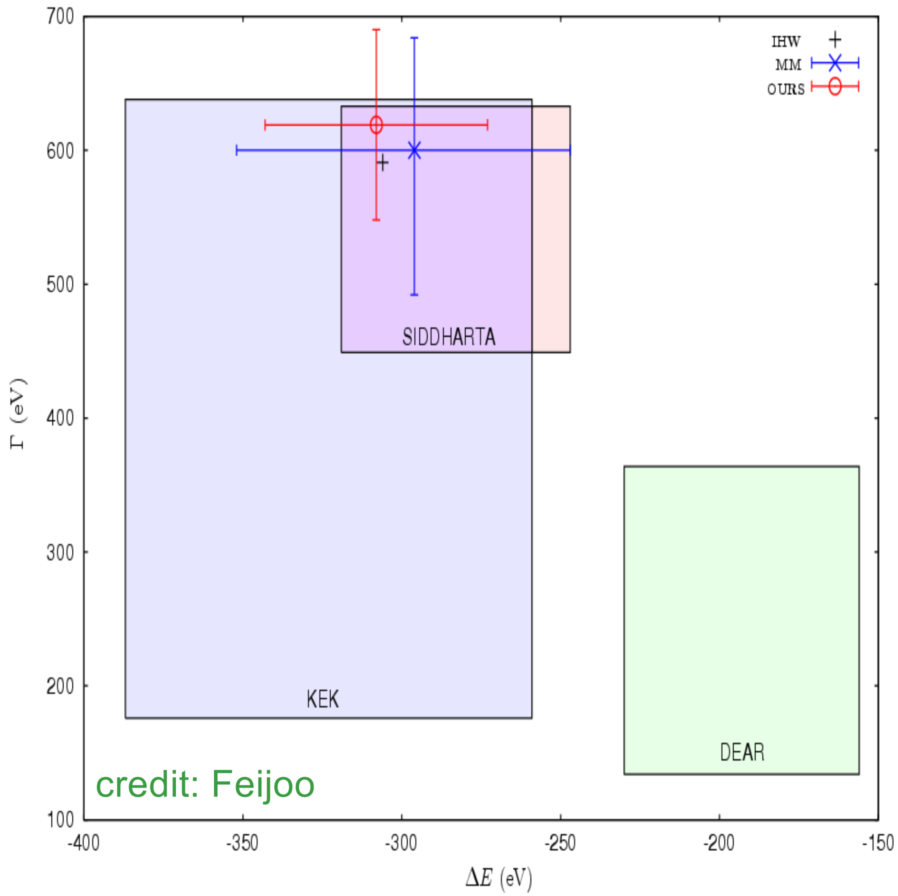
experiment theory

Scattering length

$$a_l \propto T_{if}$$

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

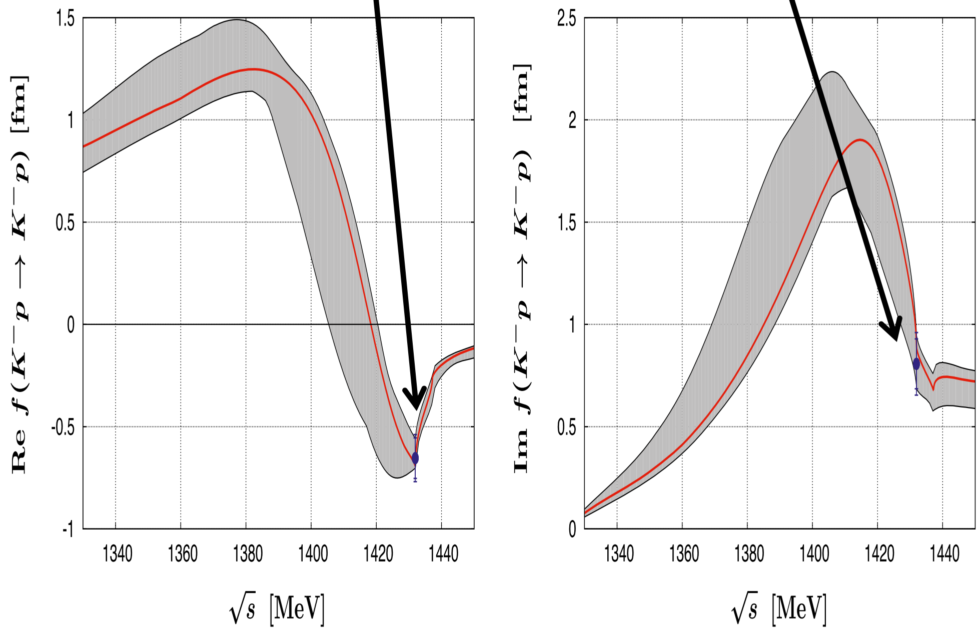


$$\Delta E - i\Gamma/2 = -2\alpha^3\mu_r^2 a(K^-p)[1 + 2\alpha\mu_r(1-\ln\alpha)a(K^-p)]$$

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)

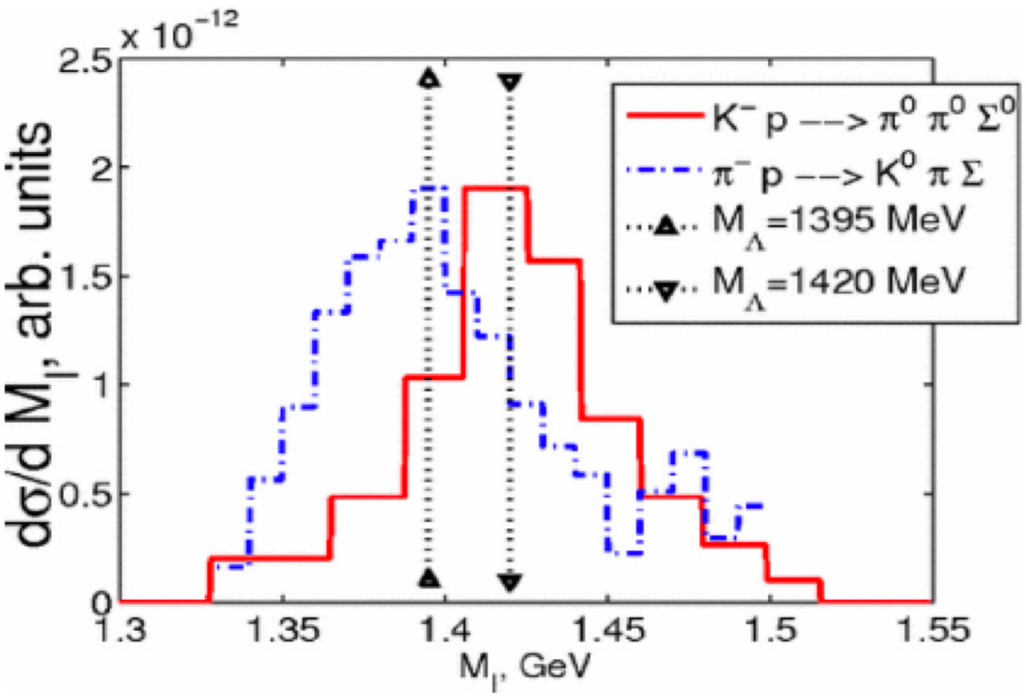
Λ(1405) results from the superposition of two poles in the complex plane, with different coupling to πΣ and $\bar{K}N$ states

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

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

PDG

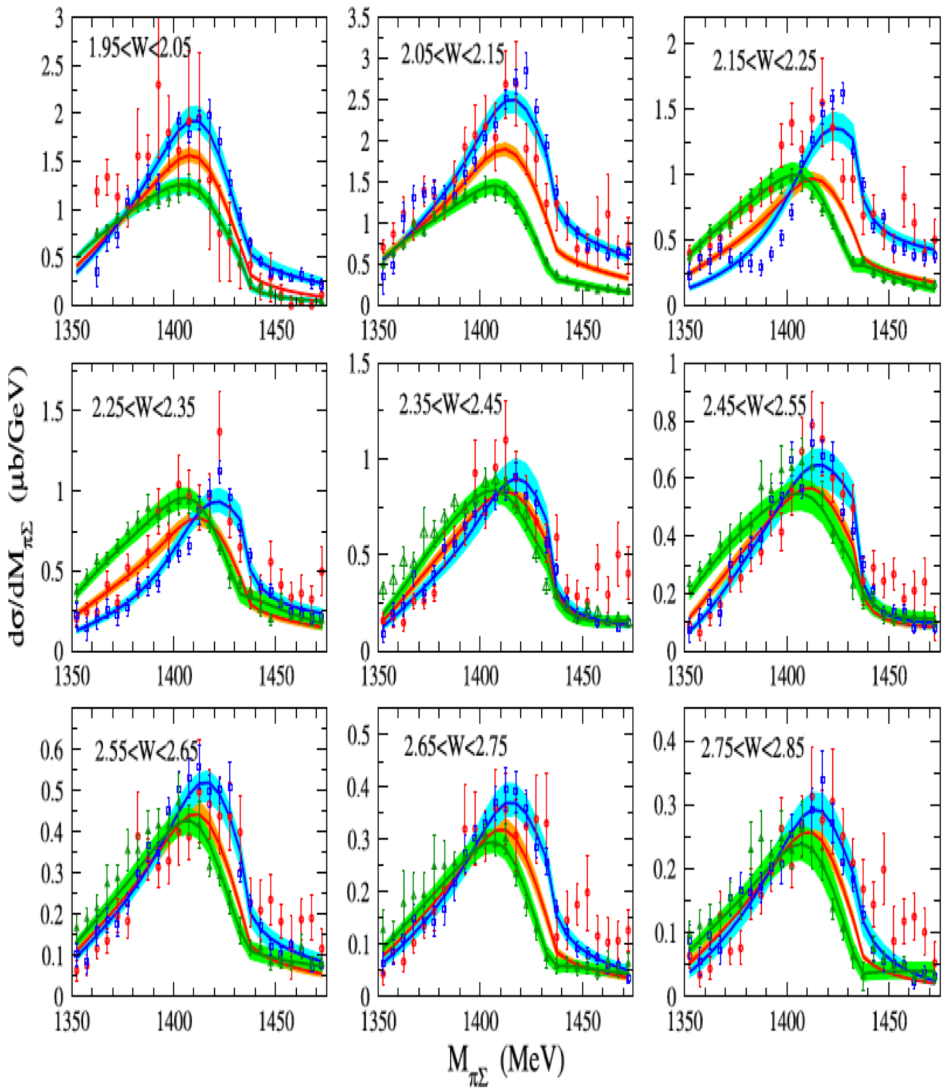
Model		First Pole [MeV]	Second Pole [MeV]
NLO	Ikeda, Hyodo and Weise ‘12	$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
Fit II	Guo and Oller ‘13	$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
Solution Nr. 2	Mai and Meissner ‘15	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$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



comparison of 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



Fit to photoproduction data, 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

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

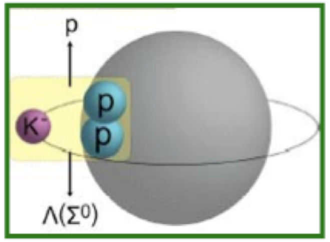
Theory: Jido, Oset and Sekihara '09 '13, Miyagawa and Haidenbauer '12, Ohnishi et al '16, Miyagawa, Haidenbauer and Kamada '18..

Proton-proton collisions

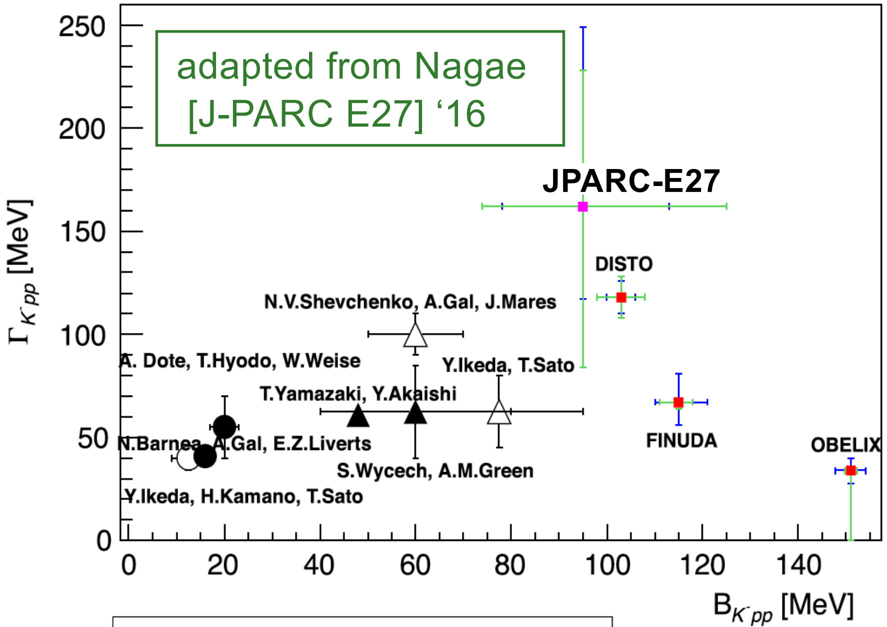
ANKE Zychor et al '08 $\boxed{pp \to pK^+\Lambda(1405)}$

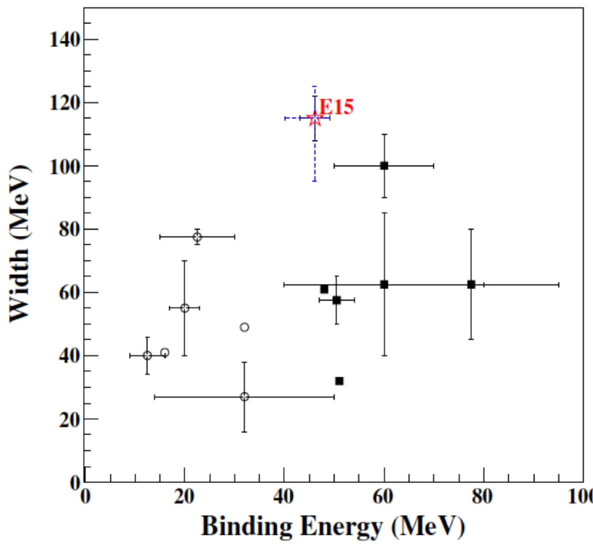
Theory: Geng and Oset '17..

$\bar{K}NN$ 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

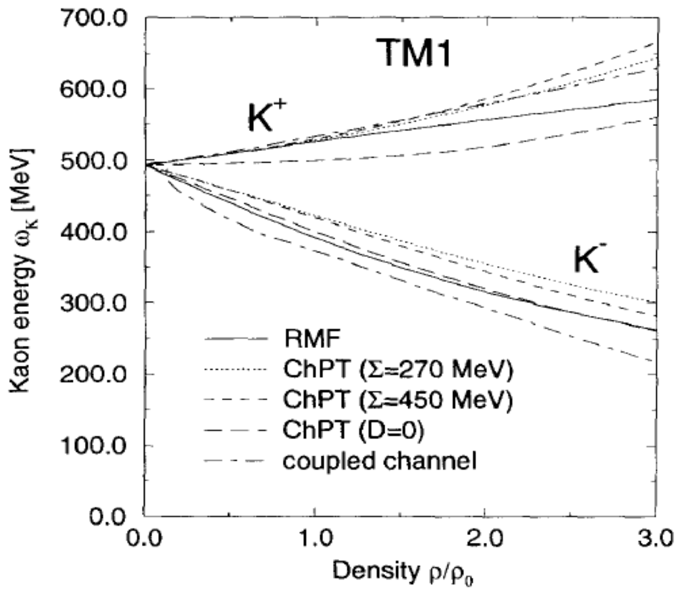
Since no baryonic resonances with positive strangeness exist (assuming no pentaquarks), the KN interaction at low densities can be described by

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

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)

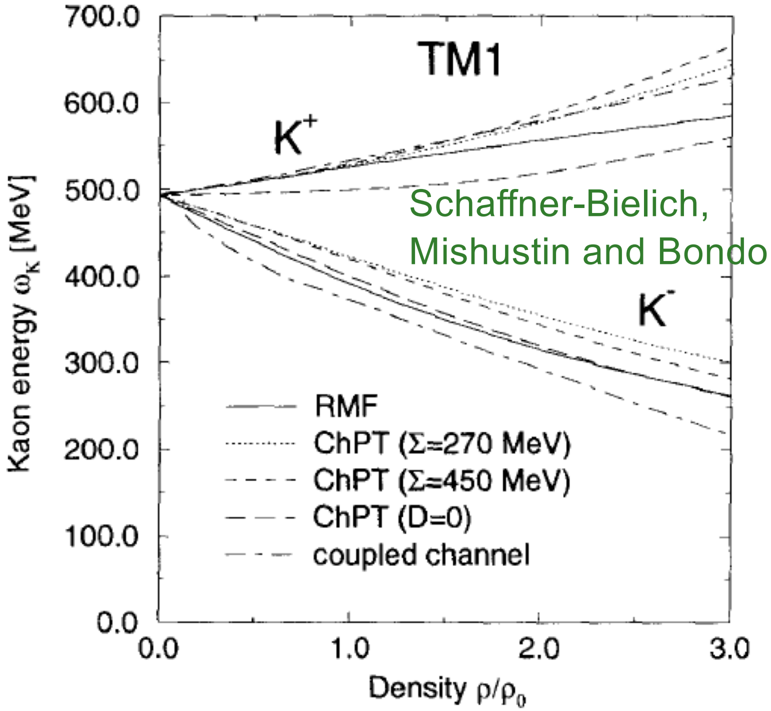
repulsive potential ~20 MeV at ρ_0 Tsushima et al. '98

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…

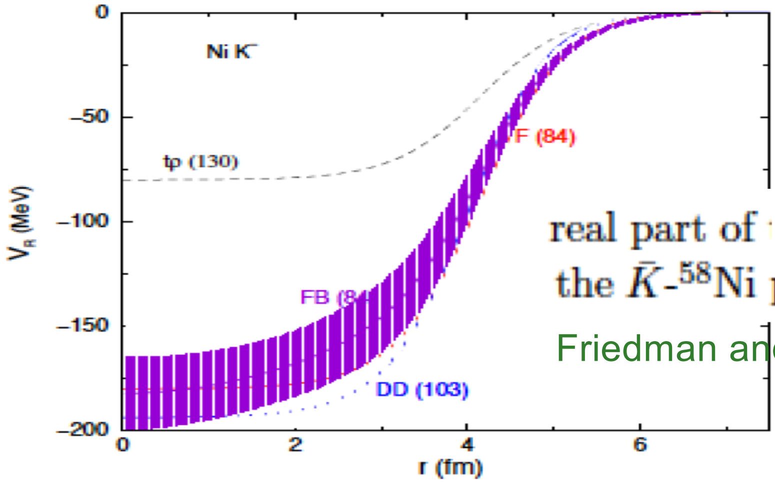
RMF: early works based on meson-exchange picture or the chiral approach for the $\bar{K}$N interaction on the mean-field level and fit the parameters to the $\bar{K}$N scattering length



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

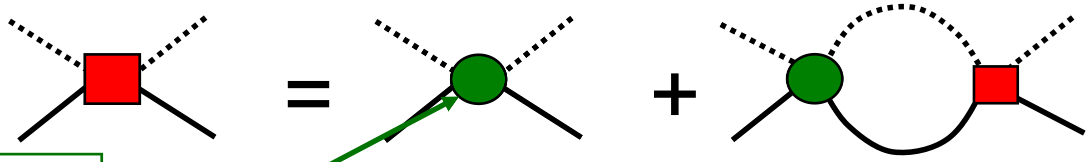
recent K^-N scattering amplitudes from χSU(3) EFT supplemented with phenomenological terms for K^- multinucleon interactions:
kaonic atoms test densities $\rho < \rho_0$

Friedman and Gal '17

Unitarized theory in matter:

selfconsistent coupled-channel procedure

Free space

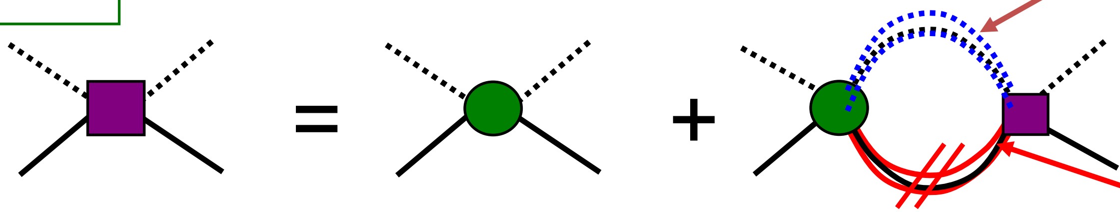


potential from chiral dynamics or meson-exchange models

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

meson dressing

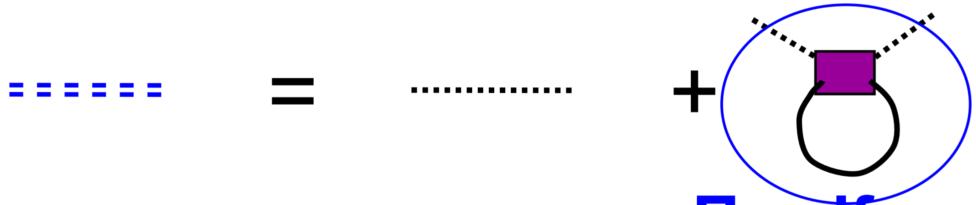
Medium



Pauli blocking and baryon dressing

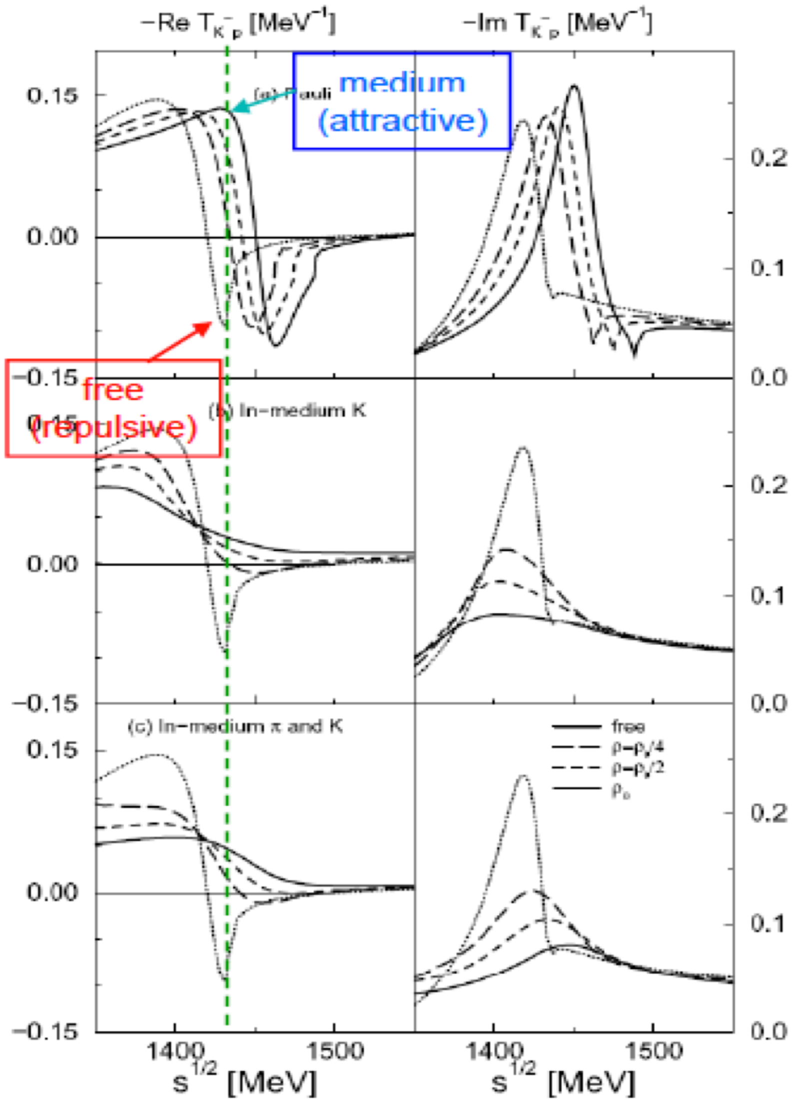
$$T_{ij}(\rho,T) = V_{ij} + V_{il}\, G_l(\rho,T)\, T_{lj}(\rho,T)$$

Dressed meson:

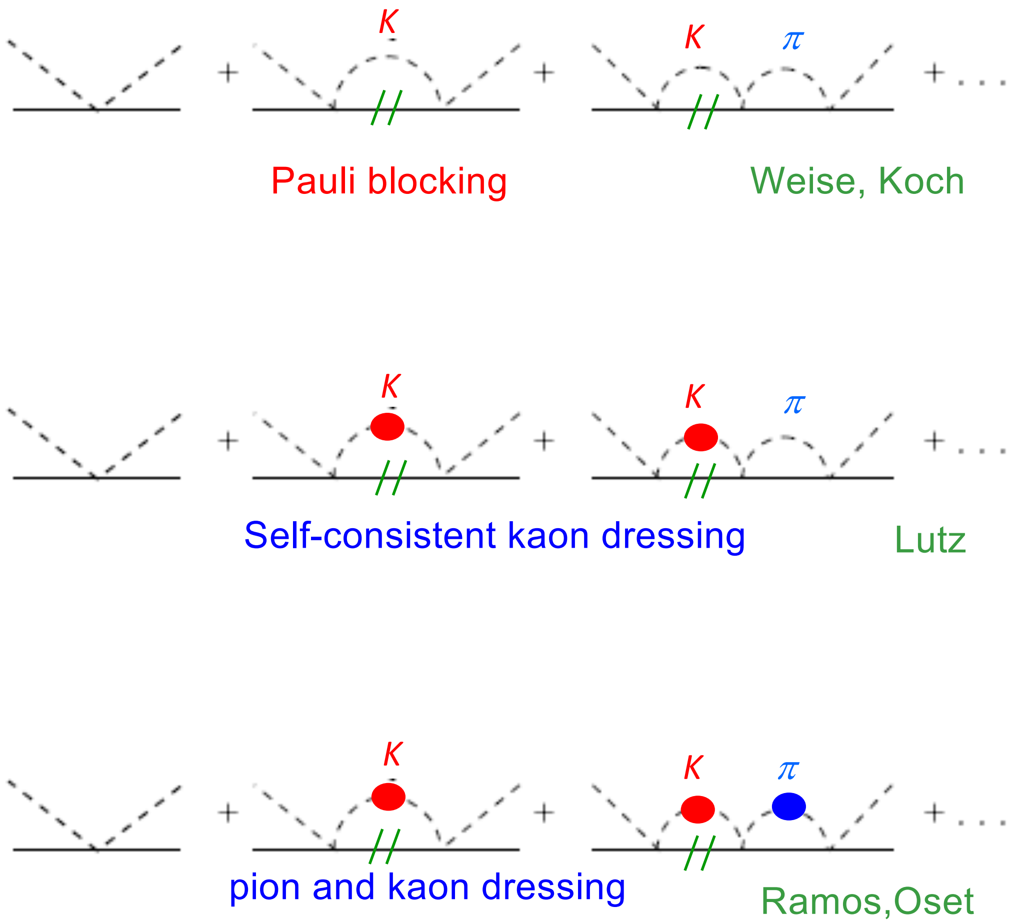


Π self-energy

The presence of the $\Lambda(1405)$ 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)



Important quantities:

Self-energy (what we calculate!)

$$\Pi_{\bar{K}}(q_0,\vec{q},T) = \int \frac{d^3p}{(2\pi)^3}\, n(\vec{p},T)\, [T^{(I=0)}_{\bar{K}N}(P_0,\vec{P},T) + 3T^{(I=1)}_{\bar{K}N}(P_0,\vec{P},T)]$$

Optical potential (non-relativistic approach, BHF type in this case)

$$E_{qp}(\vec{q}\,)^2 = \vec{q}\,^2 + m^2_{\bar{K}} + \mathrm{Re}\,\Pi_{\bar{K}}(E_{qp}(\vec{q}\,),\vec{q}\,)$$

$$U_{\bar{K}}(\vec{q}\,) = \frac{\Pi_{\bar{K}}(E_{qp}(\vec{q}\,),\vec{q}\,)}{2\sqrt{m^2_{\bar{K}} + \vec{q}\,^2}}$$

Dressed Propagator ()

$$D_{\bar{K}}(q_0,\vec{q},T) = \frac{1}{q_0^2 - \vec{q}\,^2 - m^2_{\bar{K}} - \Pi_{\bar{K}}(q_0,\vec{q},T)}$$

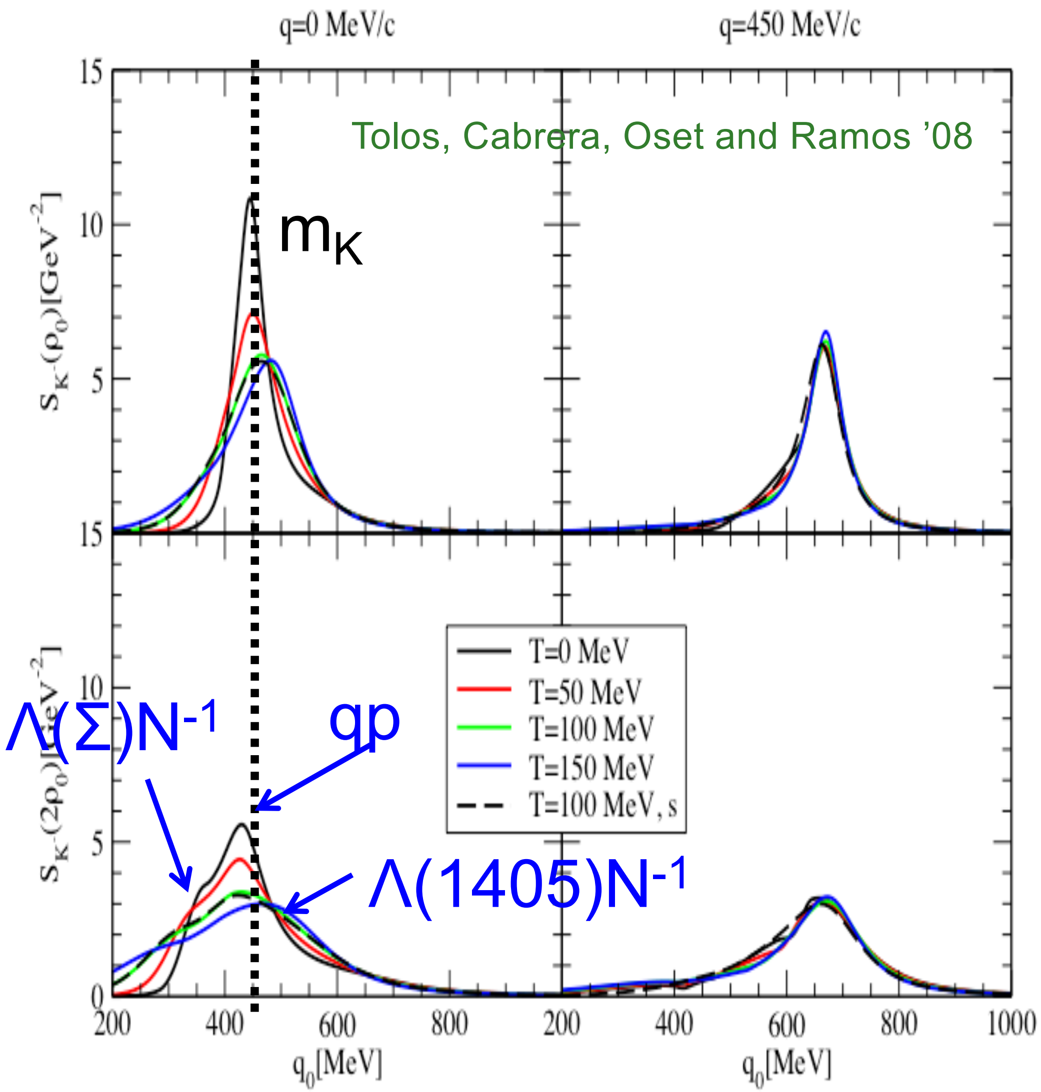
Spectral function

$$S_{\bar{K}}(q_0,\vec{q},T) = -\frac{1}{\pi}\mathrm{Im}\, D_{\bar{K}}(q_0,\vec{q},T)$$

$\bar{K}$ 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..



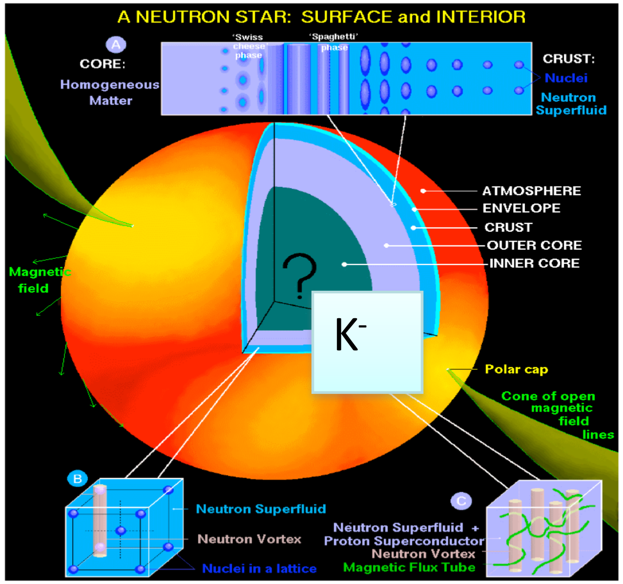
Re $U_{K^-}(\rho_0)$ ~ -50 to -80 MeV

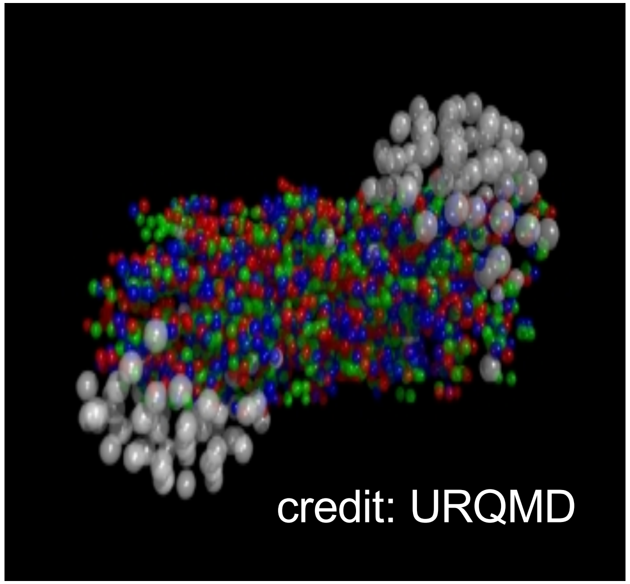
Im $U_{K^-}(\rho_0) \gtrsim$ Re $U_{K^-}(\rho_0)$

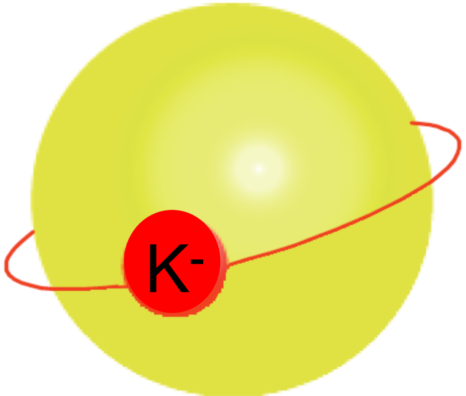
- **s-wave** $\bar{K}N$ interaction governed by $\Lambda(1405)$:
attraction due to modified $\Lambda(1405)$ in the medium using a self-consistent coupled-channel approach

- **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



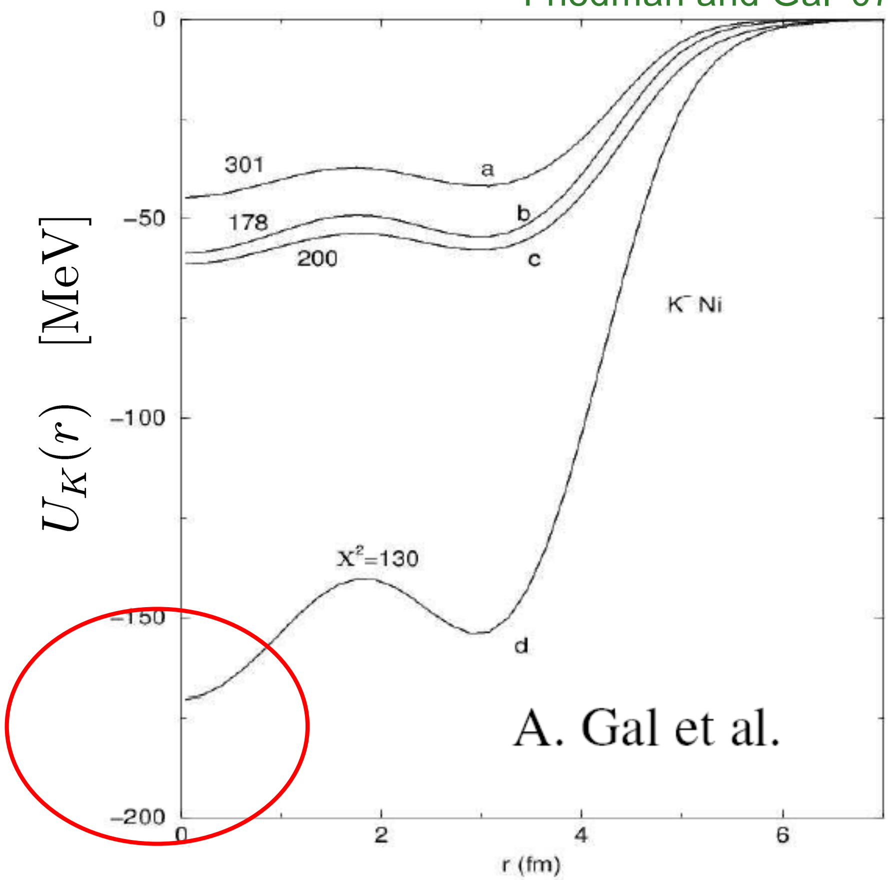




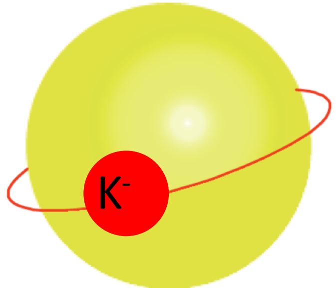
Kaonic atoms

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

Friedman and Gal '07



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

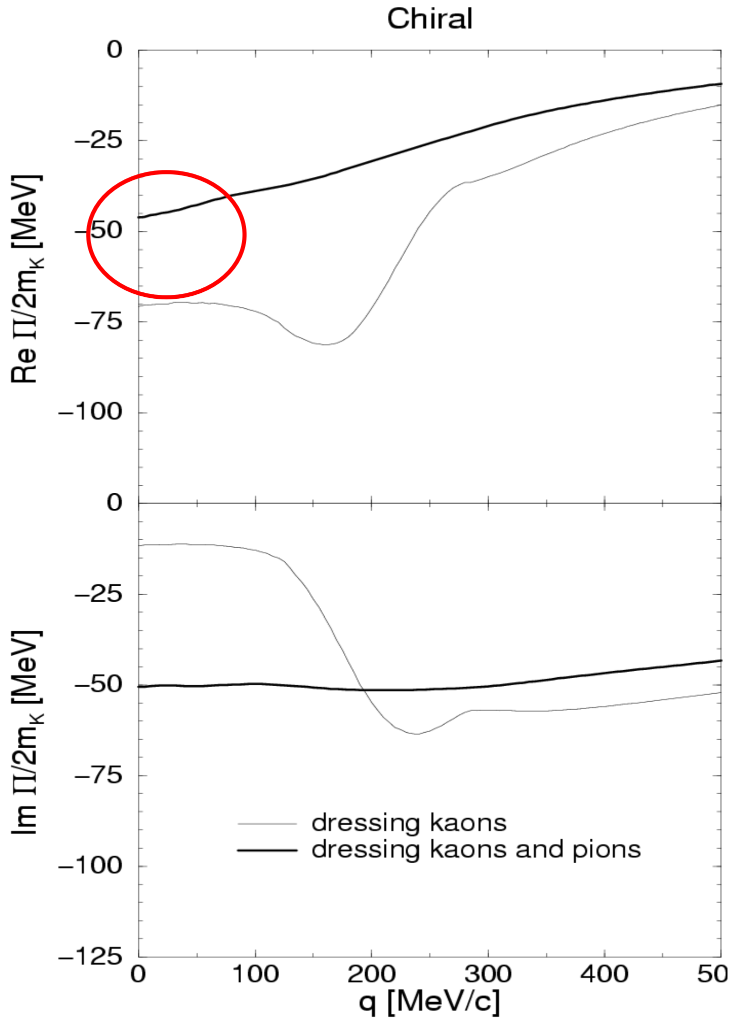


best fits to kaonic atoms seem to prefer $U_K \sim -200$ MeV at ρ_0

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

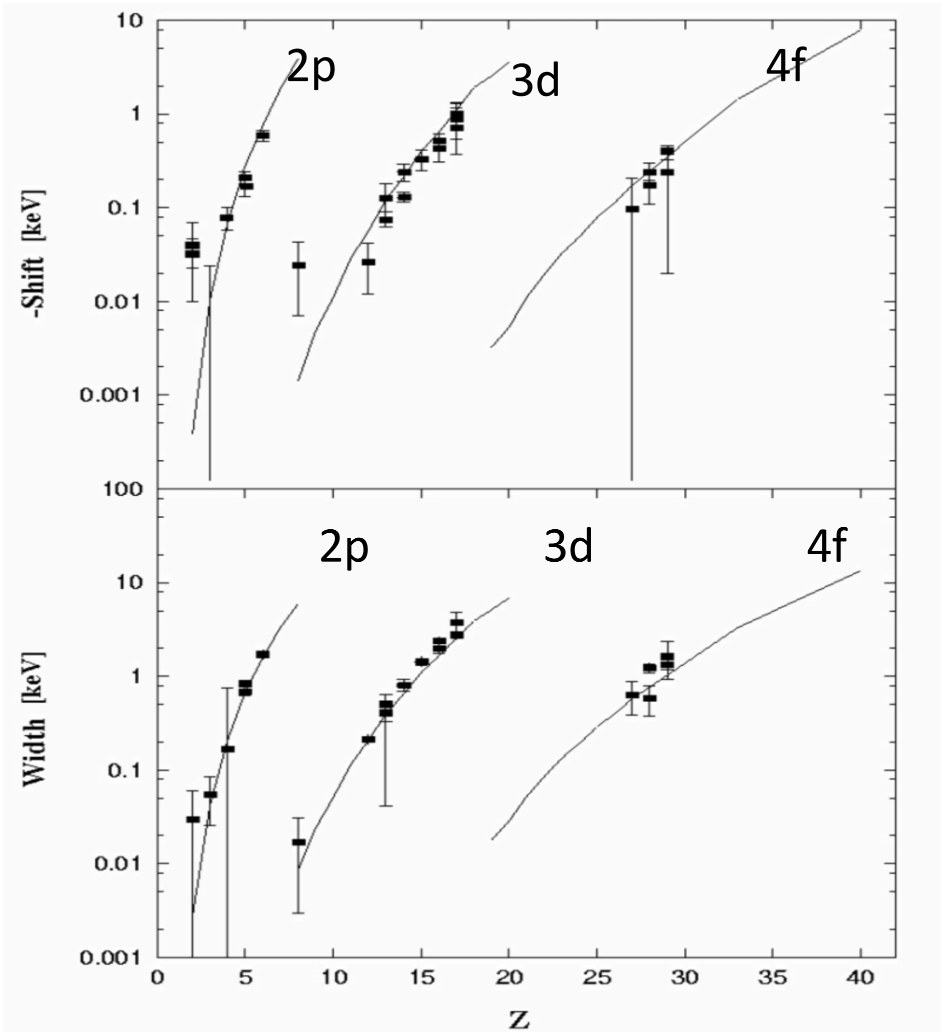
However, theoretical models based on the chiral $\bar{K}N$ interaction with many-body effects (albeit an additional moderate phenomenological piece) → moderate attraction for the K^--nucleus potential and **kaonic atoms** are also well described!!

moderate $\bar{K}N$ interaction:



Ramos and Oset '00 (chiral model)

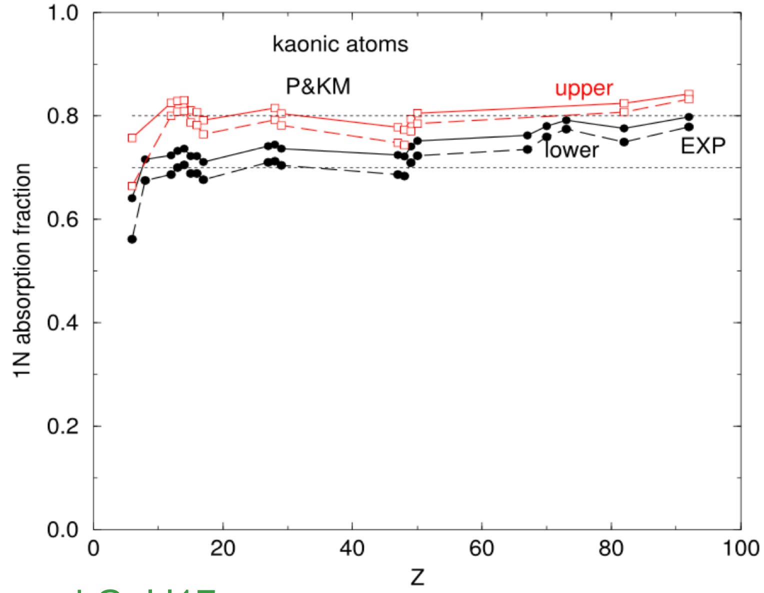
Kaonic atoms



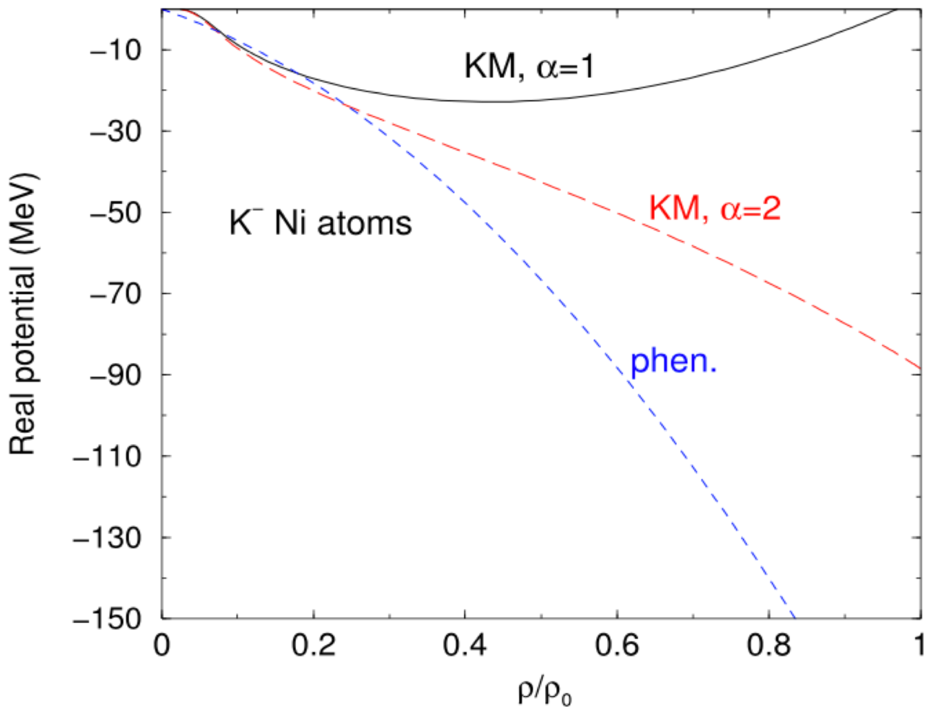
Hirenzaki et al. '00; Baca, García-Recio and Nieves '00

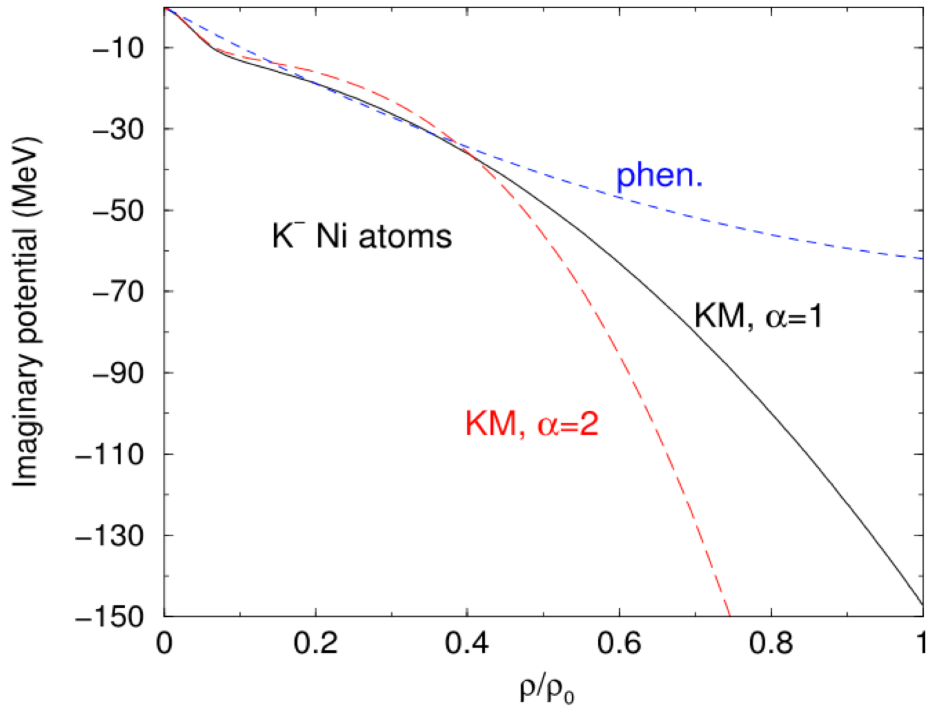
Reanalysis using chirally-motivated meson-baryon coupled-channel models supplemented with phenomenological term representing K^- multi-nucleon interactions

Friedman and Gal '17: Hrtankova and Mares '17



Friedman and Gal '17

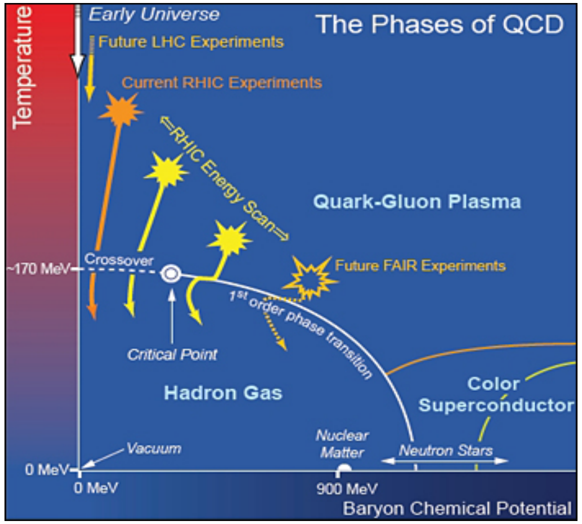




kaonic data only constrains the K^- optical potential for $\rho < 25\% \ (50\%) \ \rho_0$

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..

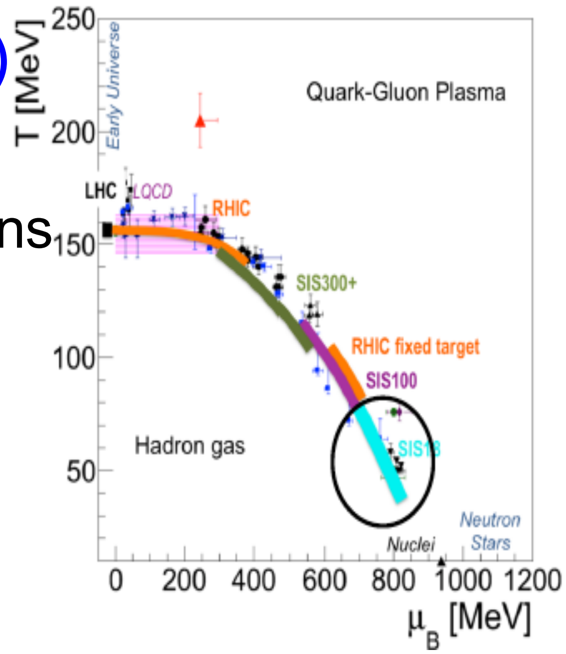
high-energy HICs:
STAR/RHIC: $K^*(892)^0$, $\phi(1020)$, Ω..
ALICE/LHC: $K^*(892)^0$, $\phi(1020)$, $\Sigma^{+-}(1385)$, $\Xi(1530)^0$..

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

More recent 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 ($\rightarrow$ 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

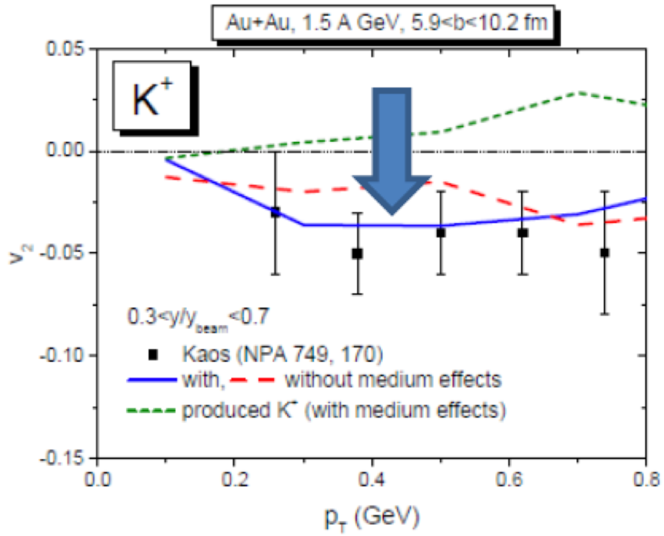
- The nuclear effects on (anti)kaon are more prominent in the collision of large nuclei

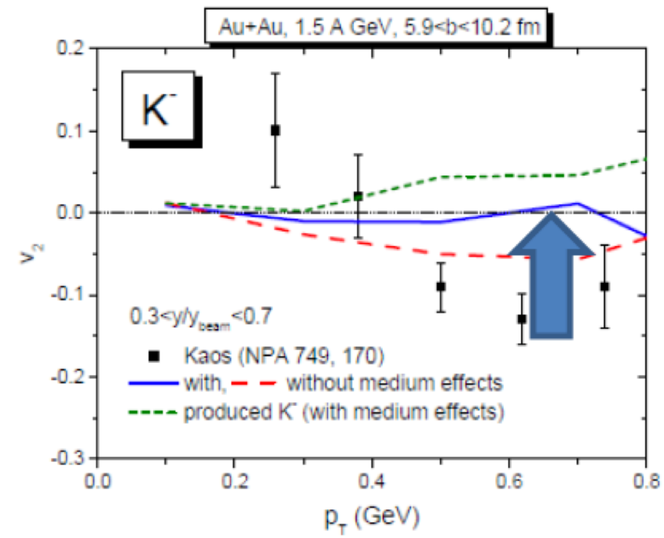
- (Anti)kaon production is (enhanced)suppressed due to (broadening of spectral function)repulsive kaon potential

- (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

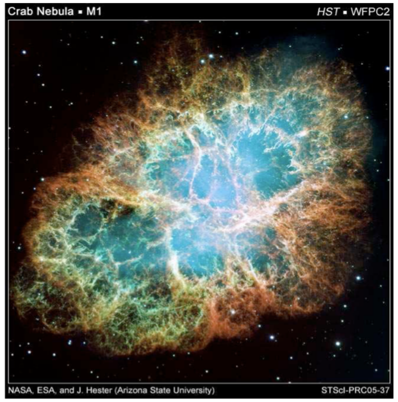
- A moderate EoS (K~300 MeV) reproduces the experimental HiC data better

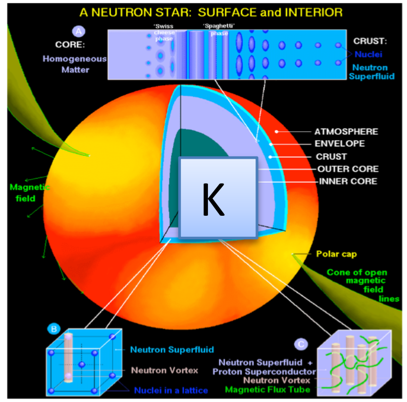




Song et al '21

Kaon condensation in neutron stars



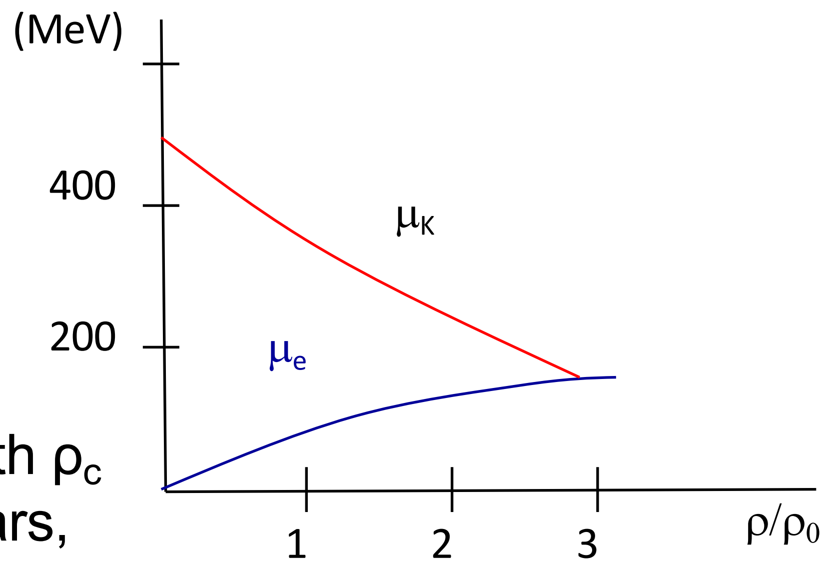


K^- feels attraction in the medium

→ 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 $\mu_{K^-} \leq \mu_{e^-}$ for $\rho \geq \rho_c$, with ρ_c being a feasible density inside neutron stars, kaons will condensate

$\bar{K}^0/K^0$ more difficult to be produced as $\mu_{K0} \leq 0$

K^+ even more difficult at $\mu_{K+} \leq - \mu_{e-}$

Glendenning '85

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

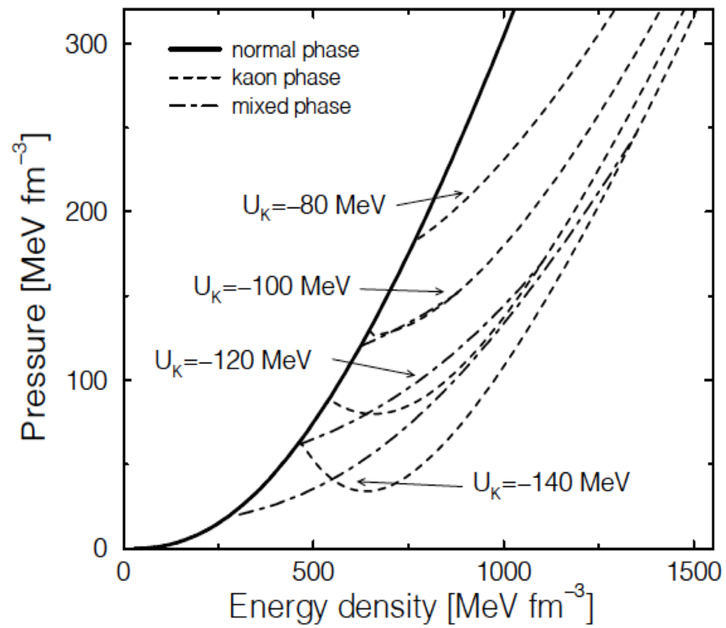
Kaplan and Nelson '86

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

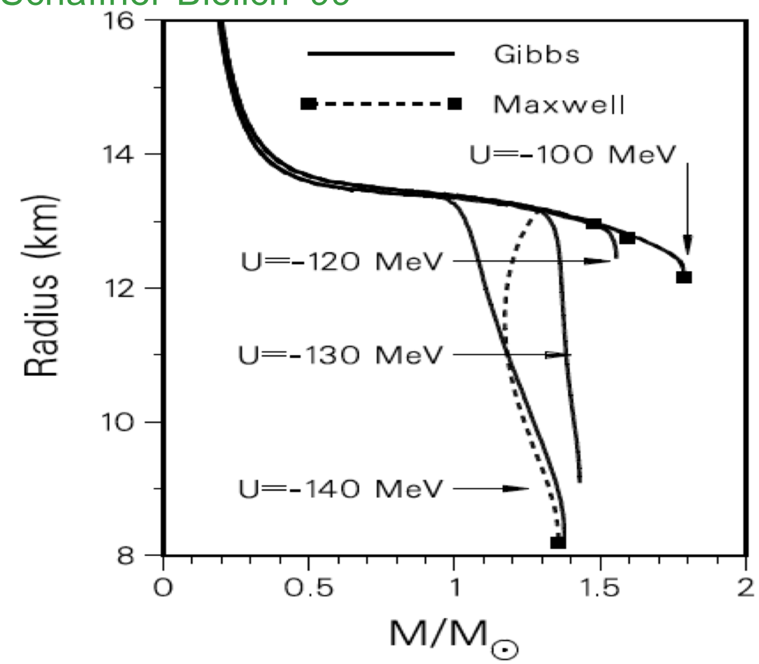
Brown, Kubodera, Rho and Thorsson'92; Thorsson, Prakash and Lattimer '94; Fujii, Maruyama, Muto and Tatsumi '96; Li, Lee and Brown '97; Knorren, Prakash and Ellis '95; Schaffner and Mishustin '96; Glendenning and Schaffner-Bielich '98 '99

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

Glendenning and Schaffner-Bielich '99



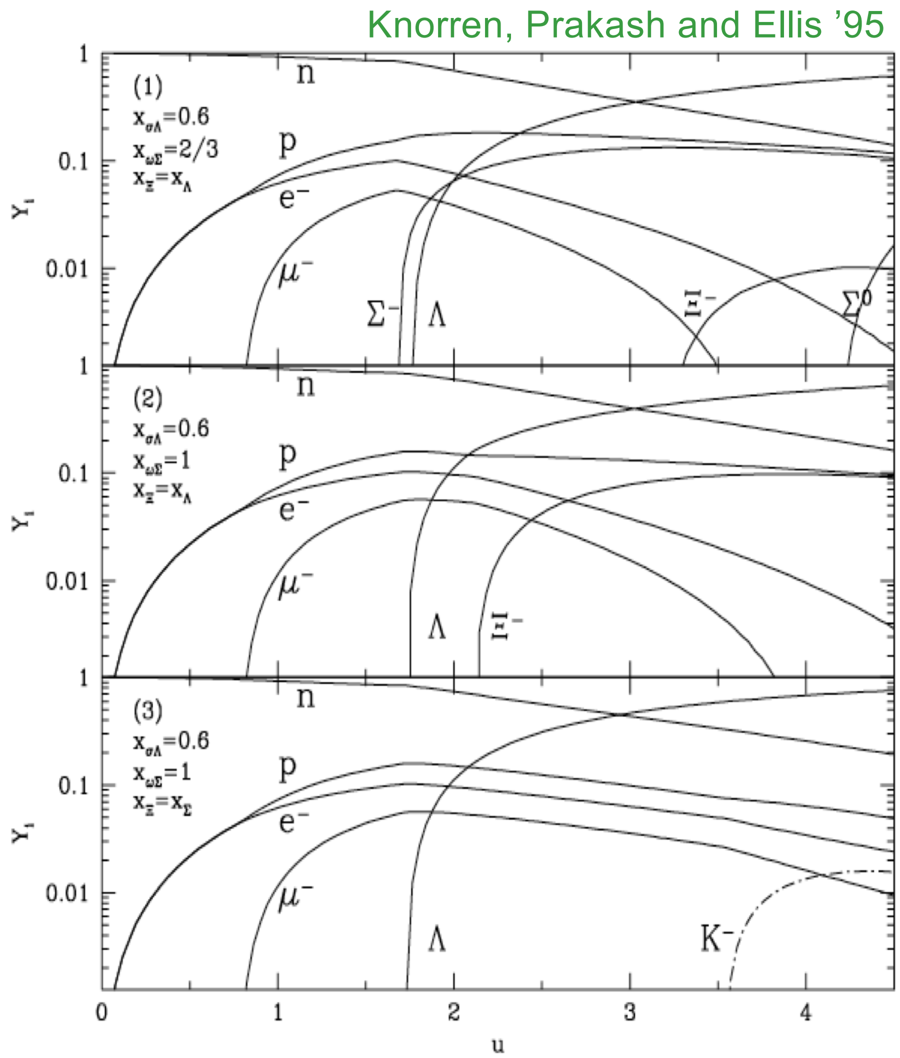
EoS is softened
due to kaon condensation



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

Effects of hyperonization on kaon condensation

Knorren, Prakash and Ellis '95



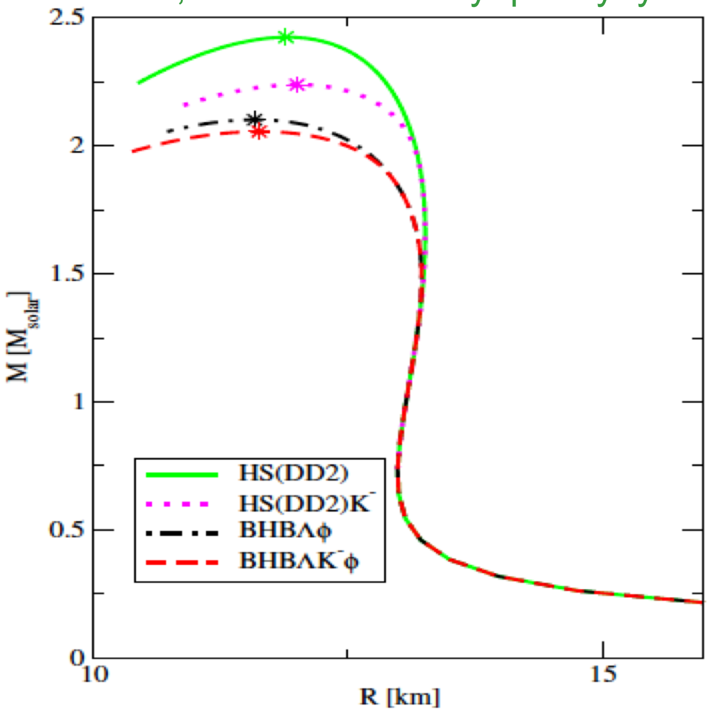
electron fraction decreases once hyperons appear, thus, the presence of hyperons increases the critical density for kaon condensation

Later on different groups have worked on improved relativistic-mean field models (with density-dependent or higher-order couplings, with or without hyperons, including three-body forces..), 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, hyperons and kaon condensate

Malik, Banik and Bandyopadhyay ‘21

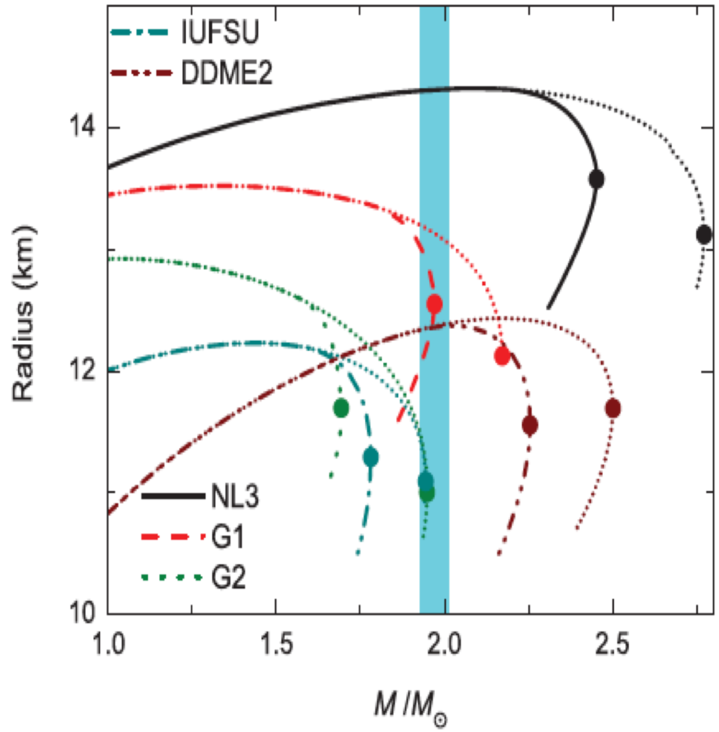


Antikaon potential at saturation density deeper than -120 MeV

Gupta and Arumugam ‘12 ‘13

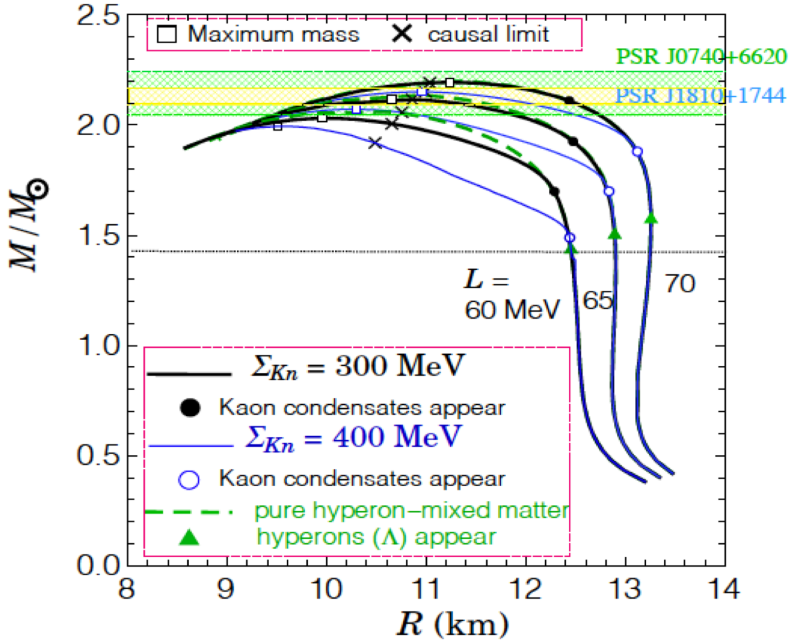
RMF effective models with higher-order couplings for nucleons and kaon condensate. No hyperons are considered

Gupta and Arumugam ‘13



Antikaon potential at saturation density is deeper than -140 MeV

Muto, Maruyama,
Tatsumi and Takatsuka '21



Muto '08
Muto, Maruyama, Tatsumi and Takatsuka '19
Muto, Maruyama, Tatsumi and Takatsuka '21

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

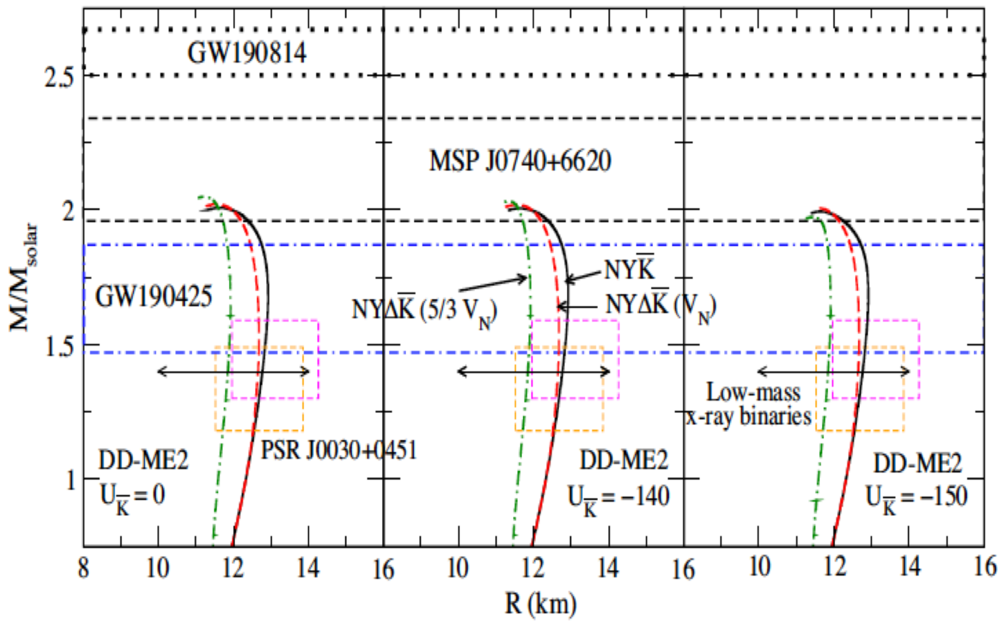
Antikaon potential at saturation density is deeper than ~ - 100 MeV

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

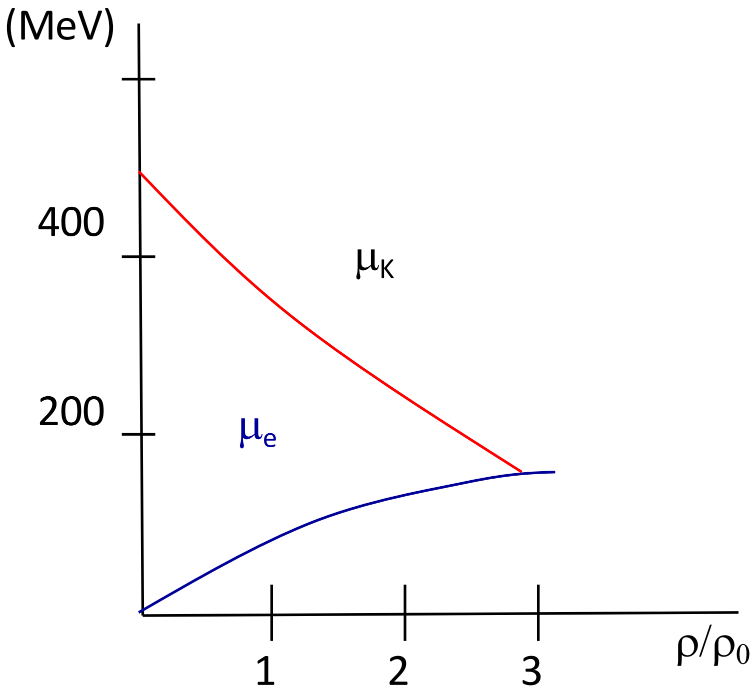
Antikaon potential at saturation density is deeper than -120 MeV

Thapa, Sinha, Li and Sedrakian '21



Using microscopic unitarized schemes…

The condition $\mu_{K-} \sim m^*_{K-} \leq \mu_{e-}$ 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

Bibliography

Laura Tolos and Laura Fabbietti,
Progress in Particle and Nuclear Physics 112 (2020) 103770

Other references mentioned in the lecture!