Hadrons in Nuclei

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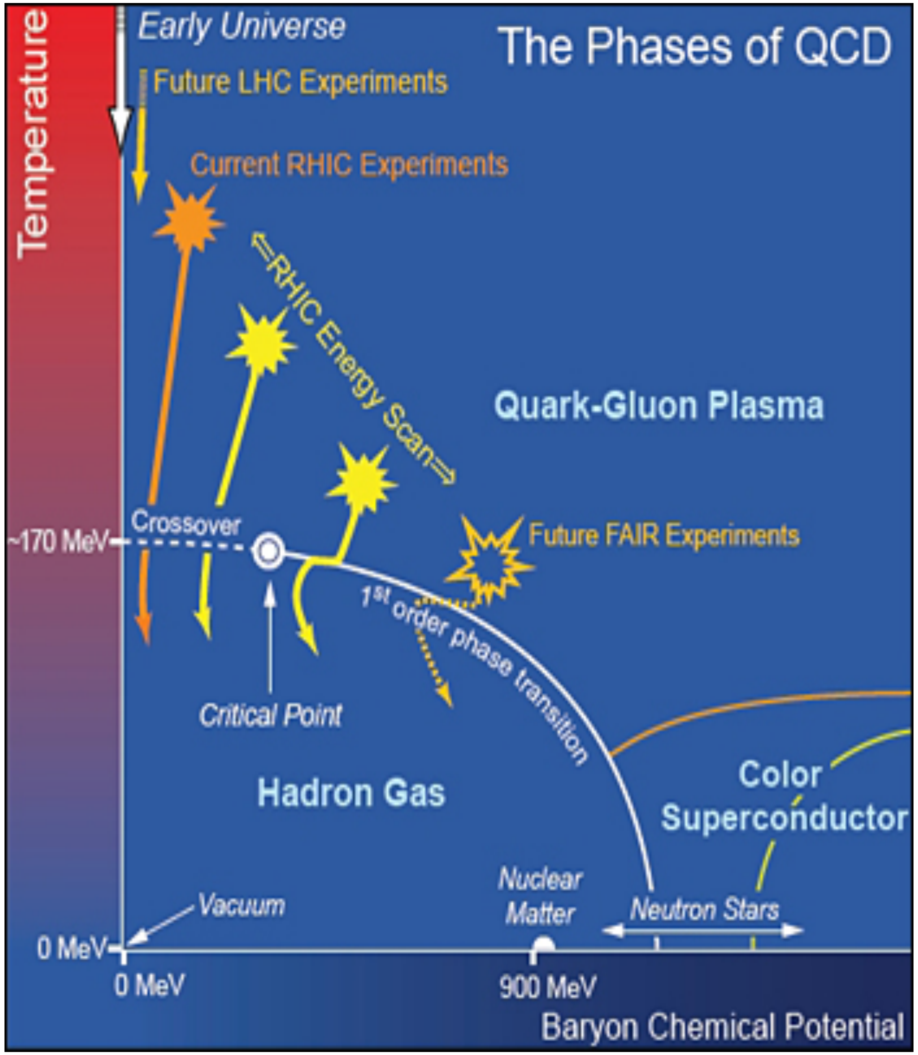
HADRON 2017

XVII International Conference on Hadron Spectroscopy and Structure

what?

understand matter under extreme conditions



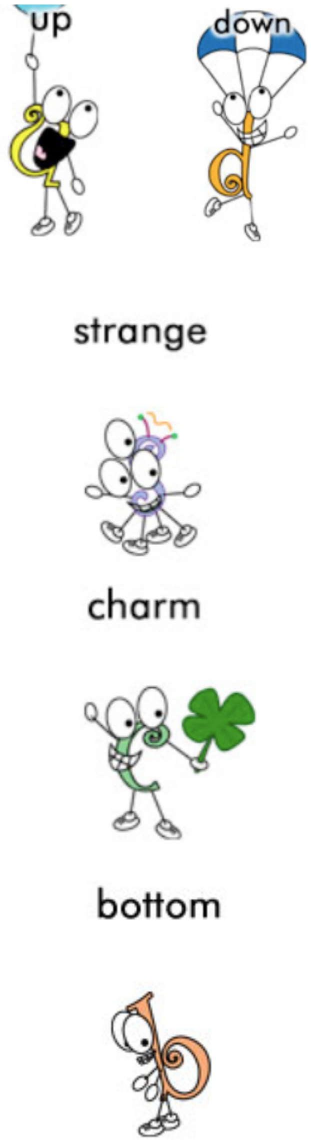
ΔE_{beam}

Pion

Kaon

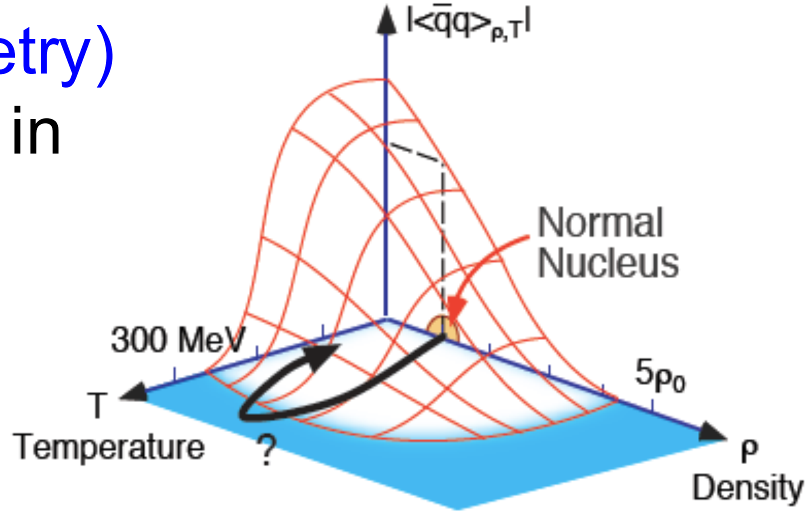
D-meson

B-meson



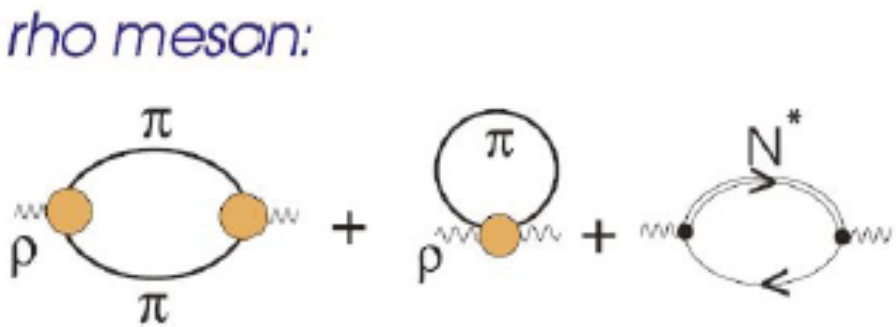
why?

• test of QCD symmetries
(chiral symmetry, heavy-quark symmetry)
for example, origin of hadron masses in the context of spontaneous chiral symmetry breaking and its partial restoration in a hadronic environment



Hatsuda et al '85, Weise et al '93

• particle phenomenology:
to understand the excitation mechanisms in the nucleus as well as the nature of those particles



if possible, separate "many body effects" from those related to QCD underlying symmetries

how?

theoretical predictions:

- RMF models
- NJL models
- QMC models
- QCD sum-rules
- effective theories
- meson-exchange models
- lattice (?)

experimentally:

photon-, electron-, neutrino-
hadron- and heavy-ion
induced reactions in nuclei

imaginary part:
transparency ratio
real part:
excitation function,
meson-momentum distribution

connecting theoretical predictions to experiments:

- transport calculations
  (GIBUU,RQMD,RBUU, IQMD, HSD, …)
- collision models based on nuclear spectral functions

Metag, Nanova and Paryev ‘17

which?

“long”-lived mesons interacting with nuclei

- π atoms

  Talk of Itahashi on Thursday

- kaonic atoms and antikaons in nuclei

  Talks of Fabietti, Gal, Iwasaki, Sekihara and Zmeskal on Tuesday

- η and η’ in nuclei

  Talks of Gal on Tuesday; Itahashi, Mares, Moskal and Nanova on Thursday

- ϕ in nuclei

  Talks of Cobos-Martinez and Ohnishi on Friday

- open and hidden charm in nuclei

  Talks of Cleven and Suenaga on Monday

which?

"long"-lived mesons interacting with nuclei

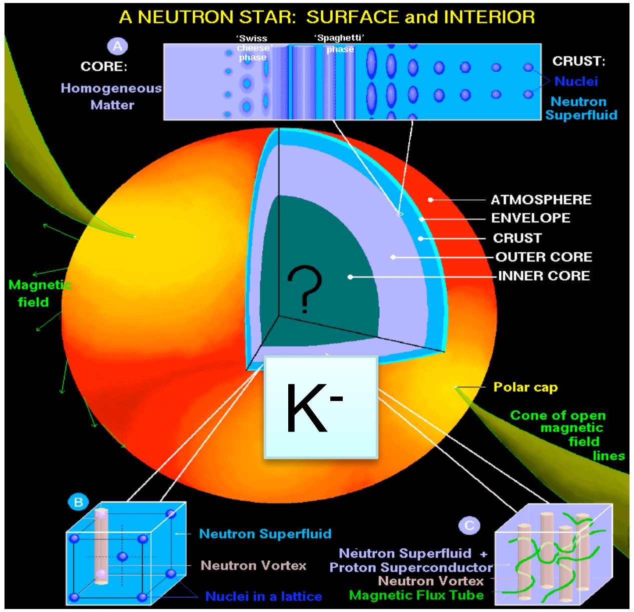
in this talk

- π atoms
- kaonic atoms and antikaons in nuclei
- η and η' in nuclei
- ϕ in nuclei
- open and hidden charm in nuclei

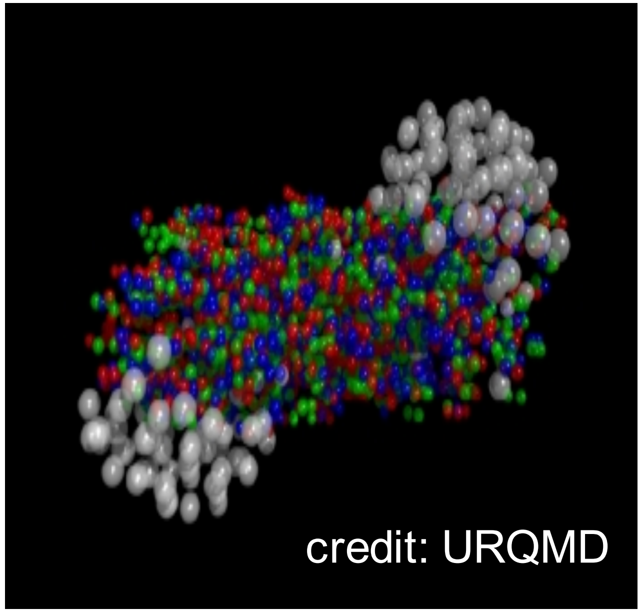
antikaons in nuclei

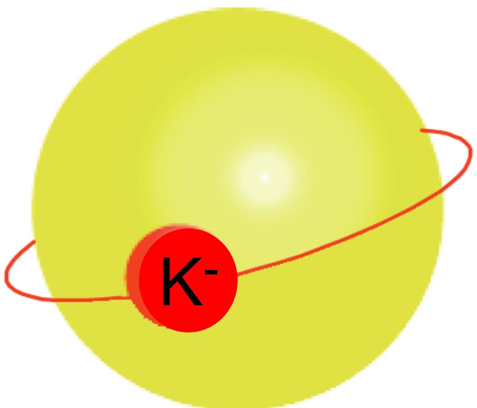
experimental and observational scenarios,
$\bar{K}N$ interaction: the $\Lambda(1405)$,
$\bar{K}NN$ state,
$\bar{K}N$ interaction in matter, and
strangeness production in HICs

experimental and observational scenarios

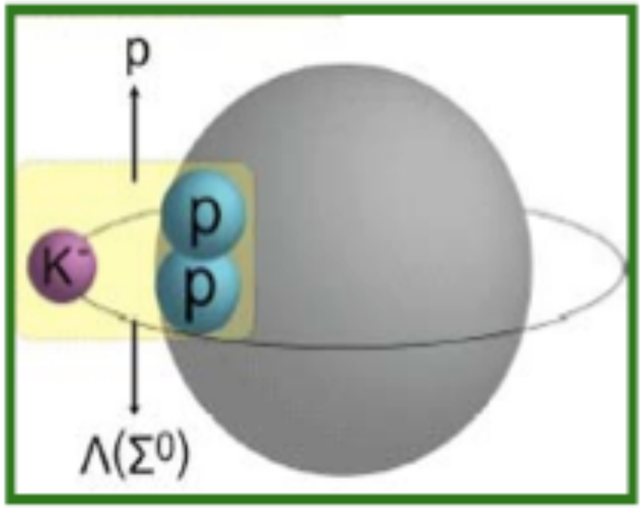


pioneer work of Kaplan and Nelson '86





review: Friedman and Gal '07

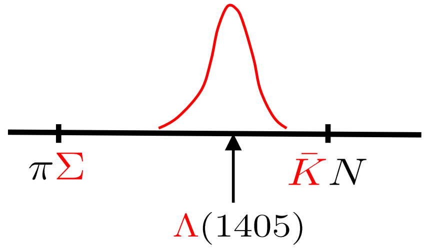


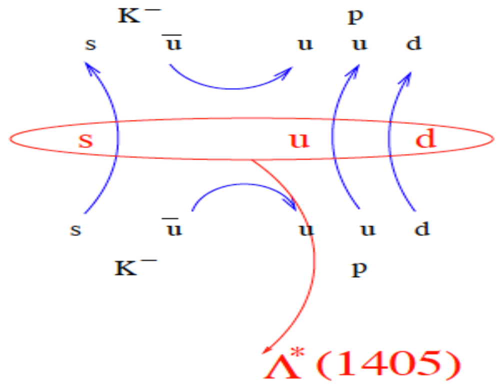
FINUDA, DISTO, OBELIX, J-PARC..

$\bar{K}$N interaction: the Λ(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 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

chiral Lagrangian

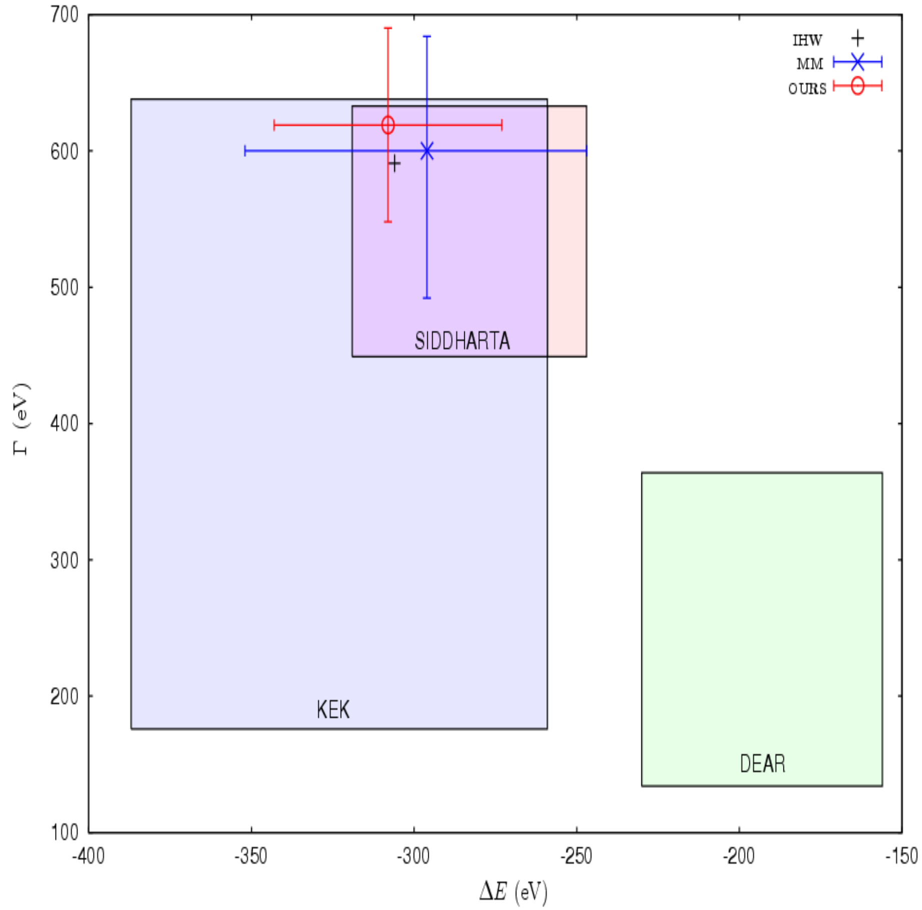
Kaiser, Siegl and Weise, '95; Oset and Ramos '98;
Oller and Meissner ' 01; Lutz, and Kolomeitsev ' 02;
Garcia-Recio et al. ' 03; Borasoy, Nissler, and Weise ' 05;
Oller, Prades, and Verbeni '05; Oller '06;
Borasoy, Meissner and Nissler '06;
Khemchandani, Martinez-Torres, Nagahiro, Hosaka '12….

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

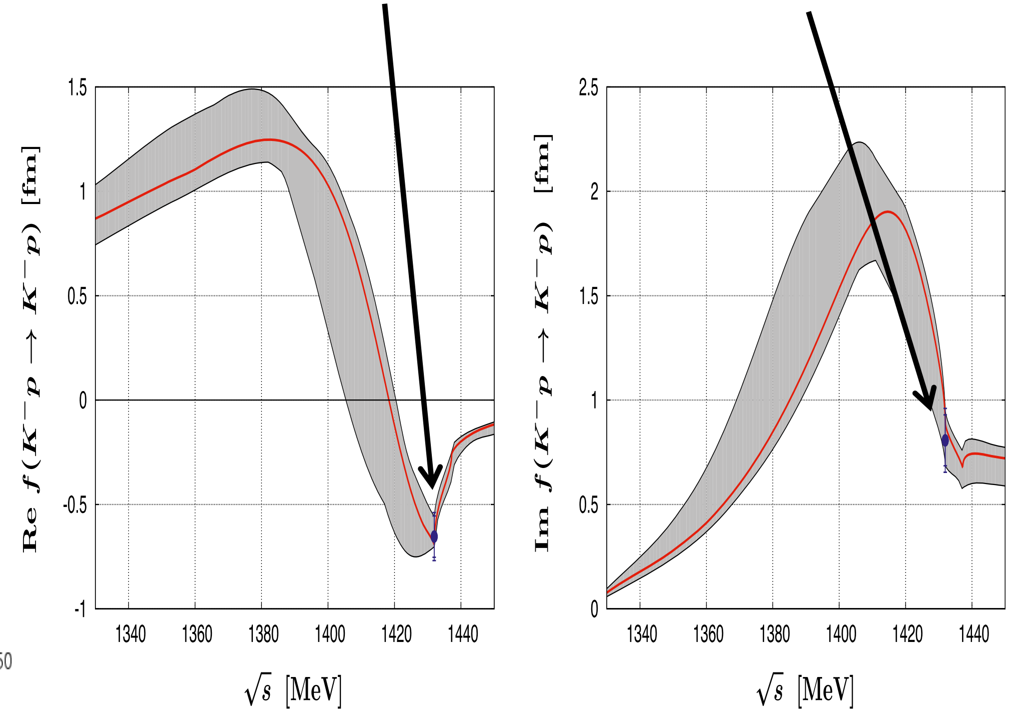
more channels,
next-to-leading order,
Born terms beyond WT
(s-channel, u-channel),
fits including new data
…

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



Bazzi et al. '11

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



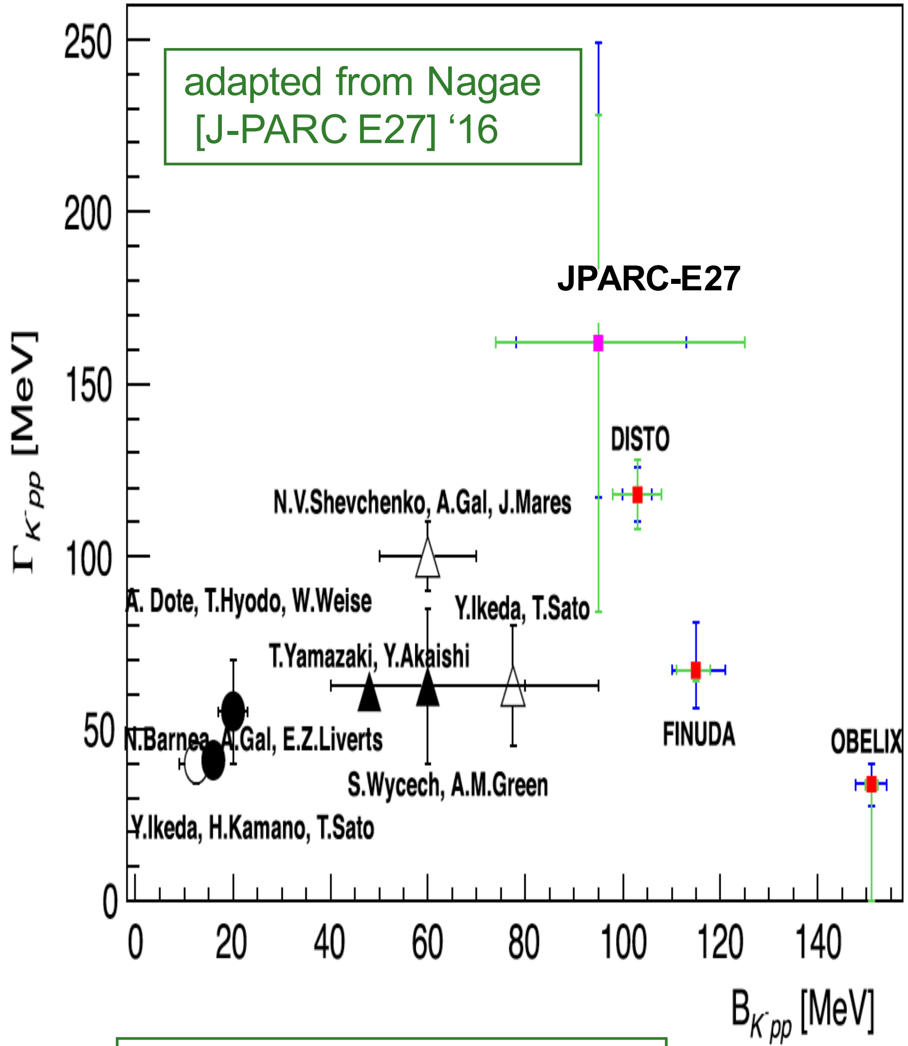
SIDDHARTA results provide important constraints on theoretical descriptions

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

$\bar{K}$NN 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



adapted from Ramos,
AMADEUS workshop '17

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

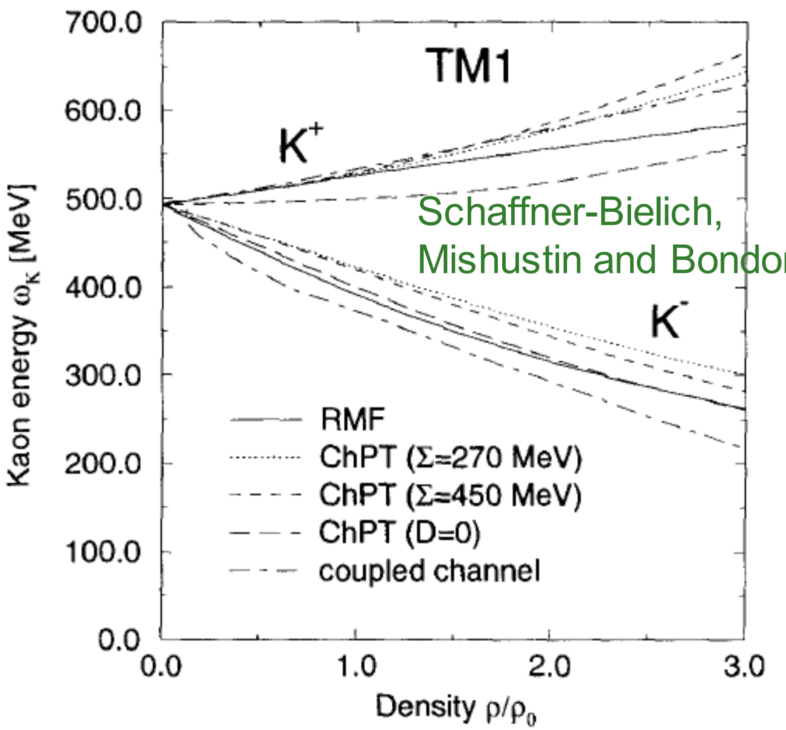
recent experiments do not find any
Tokiyasu et al. [Spring8/LEPS] '14; Hashimoto et al [JPARC E15] '15; Vazquez-Doce et al. [AMADEUS] '16
or if found Ichikawa et al [J-PARC E27] '15; Nagae et al [J-PARC E27] '16
may have other interpretation Garcilazo et al '13

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 with B~20-40 MeV Sekihara et al '16

$\bar{K}$N interaction in matter

relativistic mean-field models

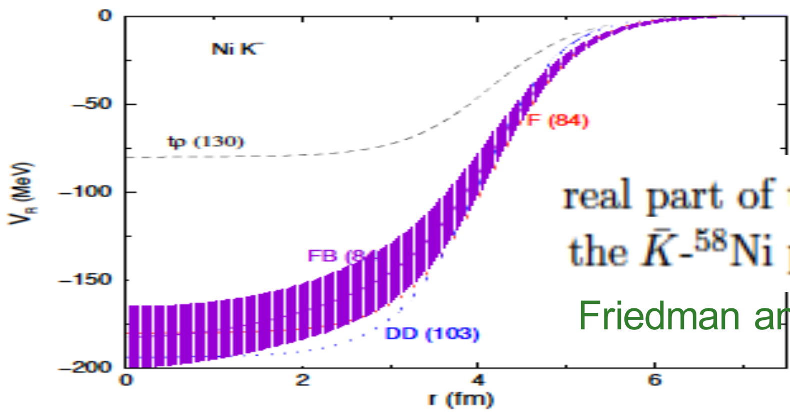
Early works on meson-exchange picture or the chiral approach for the $\bar{K}$N interaction on the mean-field level and fit the parameters to the $\bar{K}$N scattering length



Schaffner-Bielich, Mishustin and Bondorf '97

phenomenological models

density dependent potentials fitted to kaonic atoms



Friedman and Gal '07

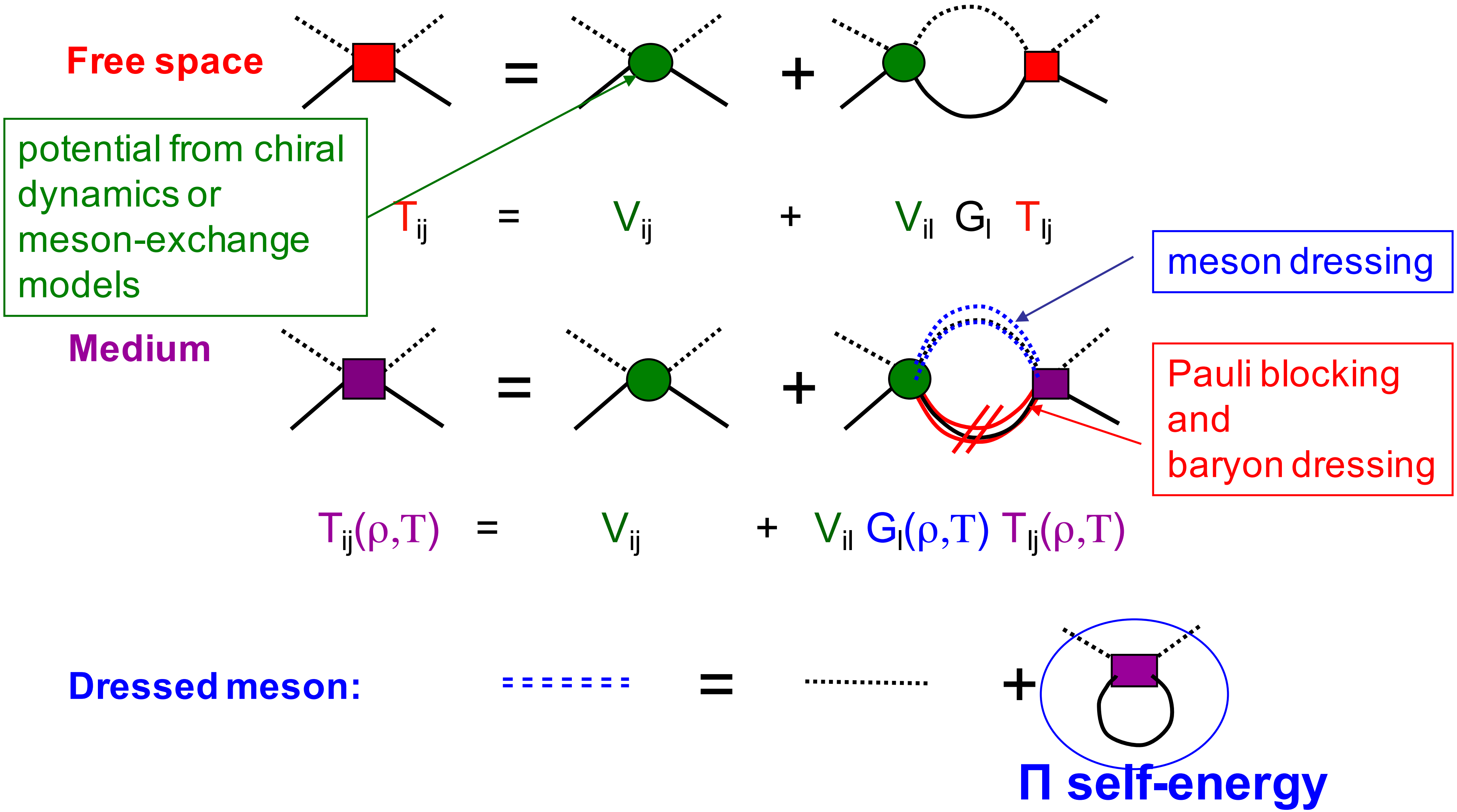
$U_{K^-}(\rho_0) \sim$ -100 to -200 MeV

recent K^-N scattering amplitudes from χSU(3) EFT supplemented with phenomenological terms for K^- multinucleon interactions: antikaonic atom data are insensitive for $\rho \geqq \rho_0$

Friedman and Gal '17

unitarized theory in matter:

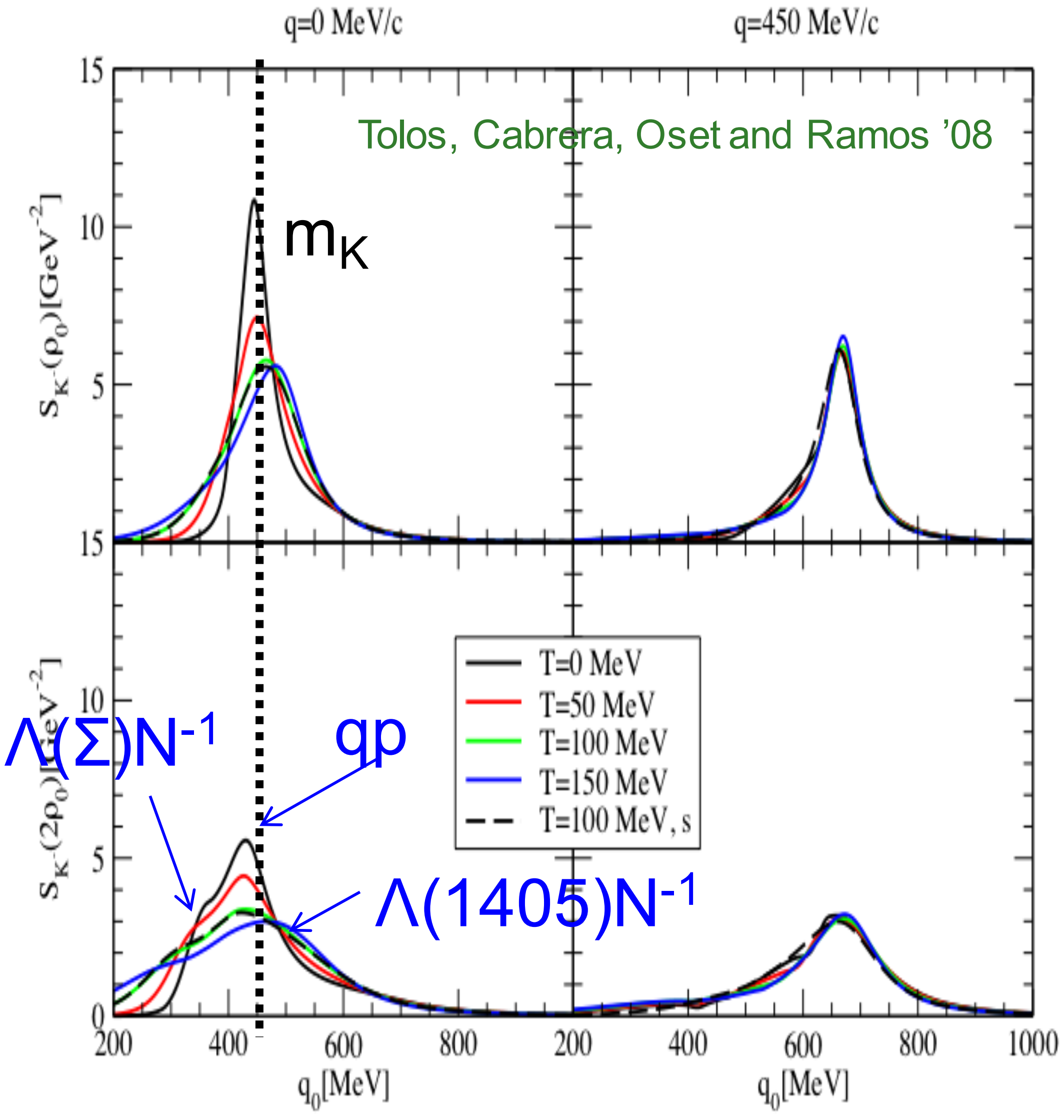
selfconsistent coupled-channel procedure



$\bar{K}$ 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

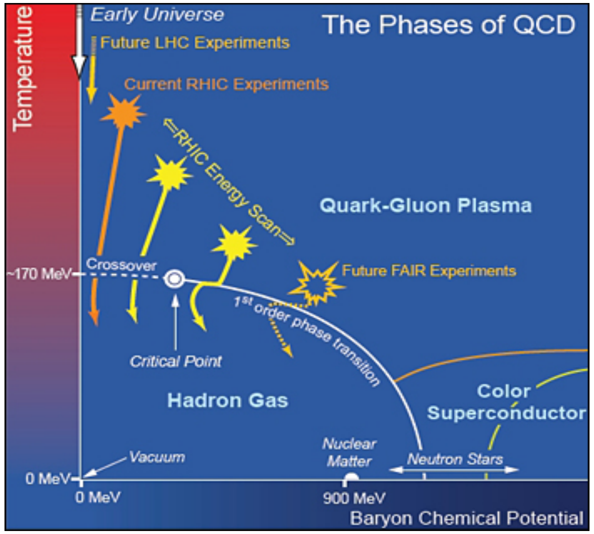
Im $U_{K^-}(\rho_0) \gtrsim$ Re $U_{K^-}(\rho_0)$

- **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 (HICs) due to large momentum

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

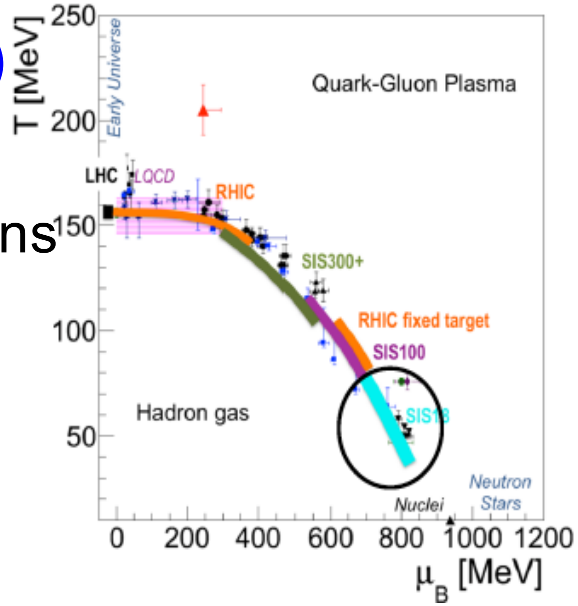
Adams et al. (STAR) ’ 05
Aggarwal et al (STAR) ’ 11
Kumar et al (STAR) ‘15
Abelev (ALICE) ’15
Adam (ALICE) ‘16
Badala (ALICE) ’ 17..

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

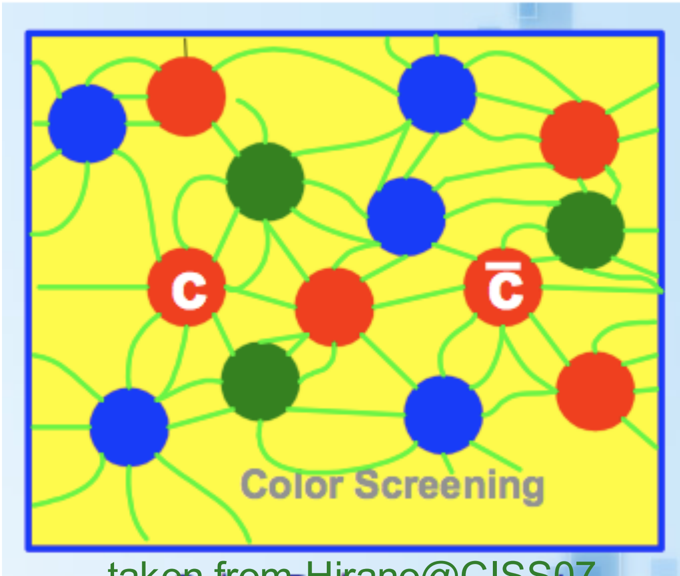
open charm in nuclei

experimental scenarios,
DN interaction: the $\Lambda_c(2595)$,
$\bar{D}N$ interaction,
DNN and $\bar{D}NN$ states,
open charm in matter, and
D-mesic nuclei

experimental scenarios

J/Ψ suppression

Gonin et al (NA50) ’96, Matsui and Satz ’86



taken from Hirano@CISS07

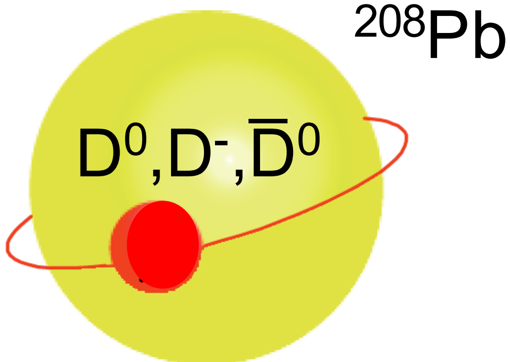
but also comover scattering

$$J/\Psi + \pi <-> D + \bar{D}$$

Capella, Armesto, Ferreiro, Vogt, Wang,
Bratkovskaya, Cassing, Andronic..

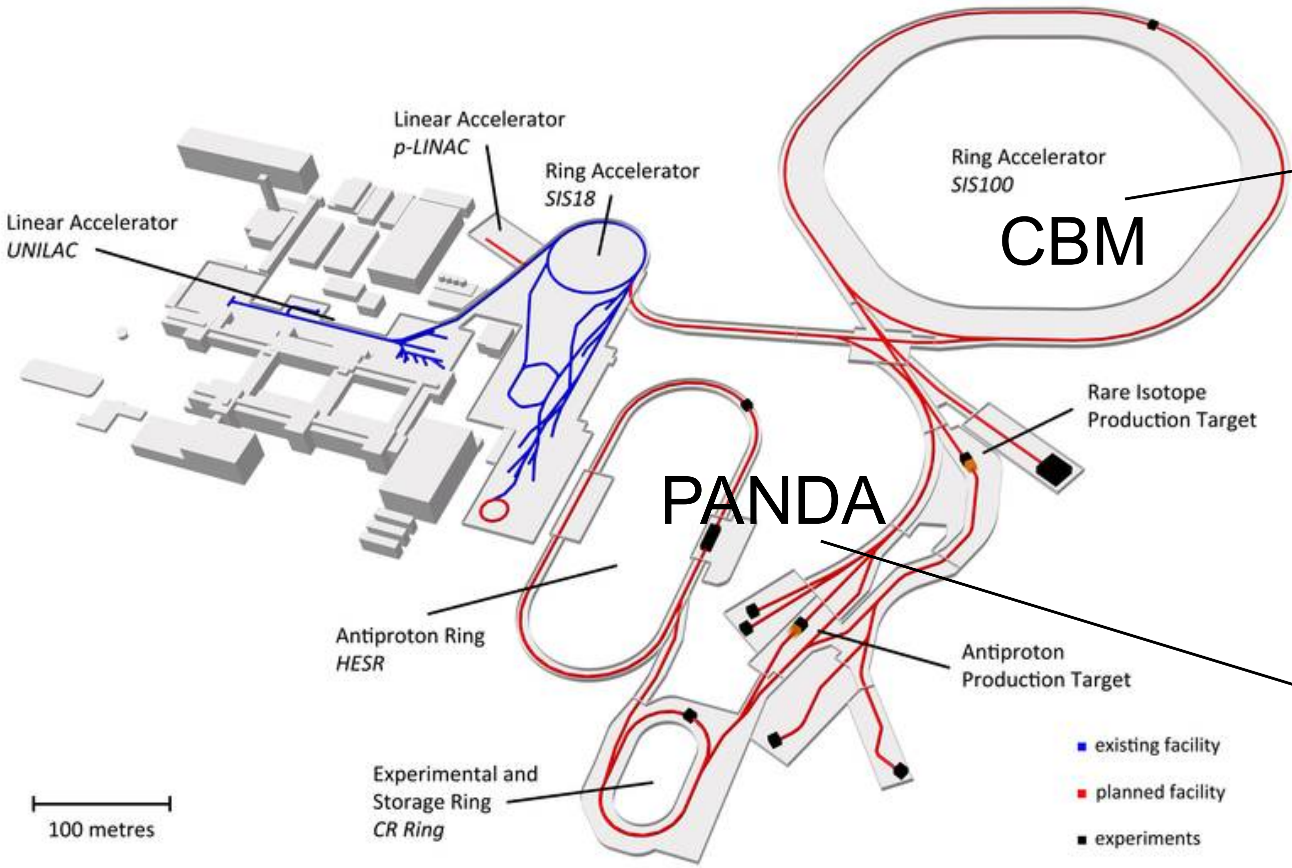
D-mesic nuclei

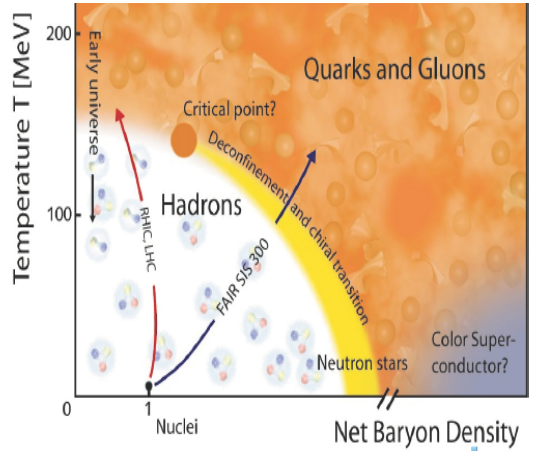
Tsushima et al ’99,
Garcia-Recio et al ’10
Garcia-Recio et al ’12
Yasui et al ’12,
Yamagata-Sekihara ‘16..

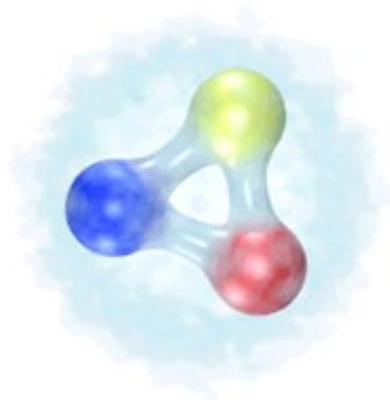


FAIR Facility for Antiproton and Ion Research

GSI



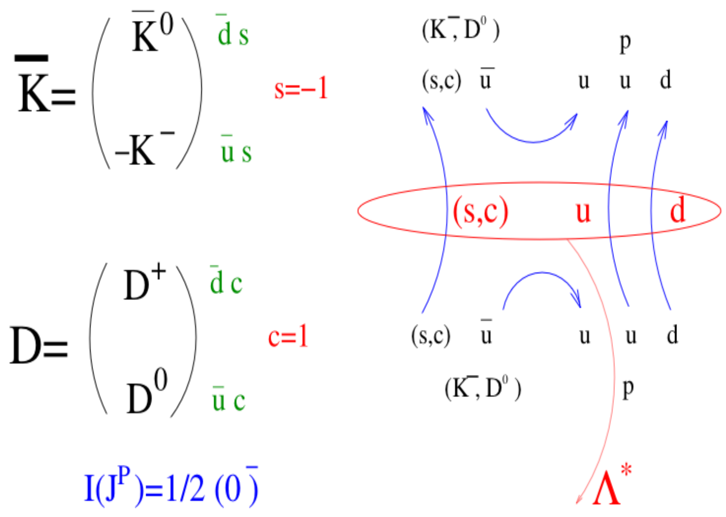




DN interaction: the $\Lambda_c(2595)$

DN interaction: similar features as $\bar{K}N$ interaction. In the charm sector we also find a subthreshold I=0 resonance, the $\Lambda_c(2595)$ (udc) with a strong resemblance to the $\Lambda(1405)$ (uds).

- Initially found within a self-consistent coupled-channel approach using a SU(3) potential for u-, d- and c- quarks Tolos, Schaffner-Bielich and Mishra ' 04
- Later on it was found using unitarized coupled-channel models based on
  - a bare interaction saturated by t-channel vector meson exchange Hofmann and Lutz '05
  - a modified t-channel vector-meson exchange in the zero-range approximation Mizutani and Ramos ' 06
  - a bare interaction incorporating heavy-quark spin symmetry (SU(6) x HQSS) Garcia-Recio, Magas, Mizutani, Nieves, Ramos, Salcedo and Tolos '09; Romanets, Tolos, Garcia-Recio, Nieves, Salcedo and Timmermans ' 12
  - a bare interaction beyond the zero-range approximation Jimenez-Tejero, Ramos, Vidana and Tolos ' 11
  - a meson-exchange model Haidenbauer, Krein, Meissner and Tolos '11
- Pion exchange model with heavy quark symmetry Yamaguchi, Ohkoda, Yasui and Hosaka ' 13; Hosaka, Hyodo, Sudoh, Yamaguchi and Yasui '17



Model	M (MeV)	Γ(MeV)
Hofmann et al '05	2593	< 1
Mizutani et al '06	2595 2625	2 103
Garcia-Recio et al '09	2595 2610	1 71
Jimenez-Tejero et al '11	2595	0.5
Haidenbauer et al '11	2594 2603	6 126
Yamaguchi et al '13	2724	-

adapted from Hosaka et al '17

$\bar{D}N$ interaction

- Using unitarized coupled-channel models based on
  - a bare interaction saturated by t-channel vector meson exchange
    Hofmann and Lutz ’05
  - a bare interaction incorporating heavy-quark spin symmetry
    Gamermann, Garcia-Recio, Nieves, Salcedo and Tolos ’10
  - a meson-exchange model Haidenbauer, Krein, Meissner and Sibirtsev ’07

- Pion exchange model with heavy quark symmetry
  Yamaguchi, Ohkoda, Yasui and Hosaka ’11; Hosaka, Hyodo, Sudoh, Yamaguchi and Yasui’ 17

- Chiral quark model
  Carames and Valcarce ‘12

charmed bound pentaquark

Model	DbarN(I=0) bound state
Hofmann et al ‘05	
Gamermann et al ‘10	2805 MeV
Haidenbauer et al ‘07	
Yamaguchi et al ‘11	2804 MeV
Carames et al ‘12	

adapted from Hosaka et al ‘17

DNN and $\bar{D}$NN states

if the DN and $\bar{D}$N interactions are so attractive, D/$\bar{D}$-nuclear clusters may form

DNN

Bayar, Xiao, Hyodo, Dote, Oka and Oset ‘12

- DN system has a quasi-bound $\Lambda_c(2595)$ in I=0 channel
- Solving 3-body problem using variational calculation and fixed center approximation to Faddeev equation

DNN quasibound state

$I=1/2$, $J=0^-$
M~ 3500 MeV
Γ ~20-40 MeV

interpreted as a quasibound state of $\Lambda_c(2595)$ and a nucleon

$\bar{D}$NN

Yamaguchi, Yasui and Hosaka ‘14

$\bar{D}$N-$\bar{D}^*$N interaction is given by pion-exchange potential and the NN interaction is adopted by Argonne v18

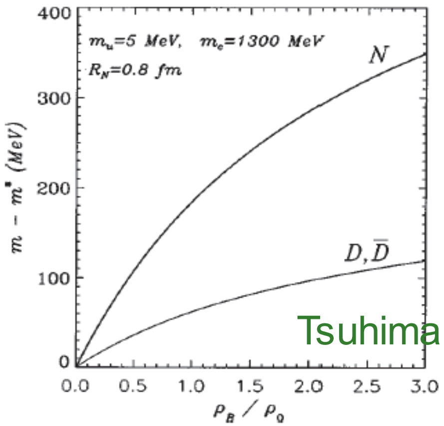
$I=1/2$, $J=0^-$:
$\bar{D}$NN bound state with 5.2 MeV binding

$I=1/2$, $J=1^-$:
$\bar{D}$NN resonance at 111.2 MeV above threshold

open charm in matter

QMC model

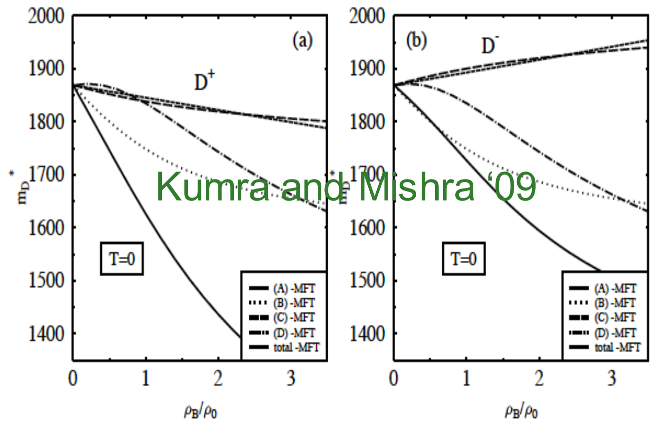
exchange of ω, ρ, σ mesons among quarks in hadron bag



Tsuhima et al '98

Tsushima, Thomas, Krein, Sibirtsev, Fountoura..

MF/RHF model



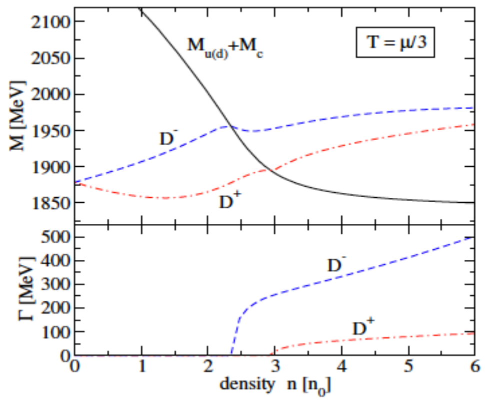
Kumra and Mishra '09

MF/RHF approach that includes charmed mesons

Mazumdar, Mishra, Kumar,..

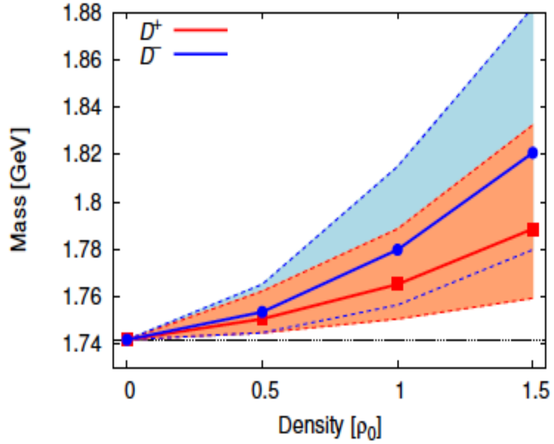
NJL model

SU(4) NJL model with Polyakov loop



Blaschke, Costa and Kalinovsky '12

QCD sum-rule

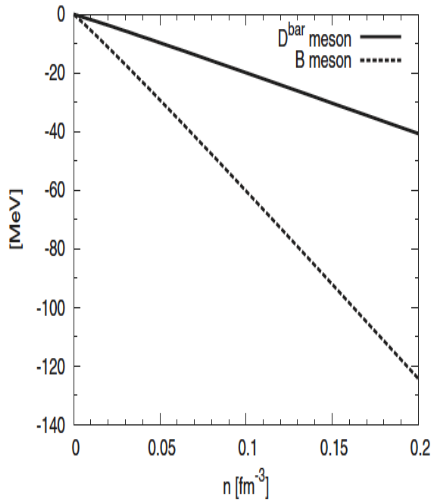


Suzuki, Gubler and Oka '15

Gubler, Hayashigaki, Hilger, Kaempfer, Leupold, Nielsen, Navarra, Oka, Suzuki, Thomas, Weise, ..

operator product expansion for in-medium correlation function and relate it to the spectral function

π exchange with HQ



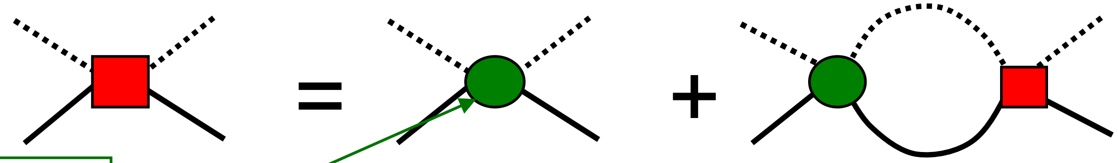
heavy meson - nucleon interaction mediated by π exchange with HQ

Yasui and Sudoh '13

unitarized theory in matter:

selfconsistent coupled-channel procedure

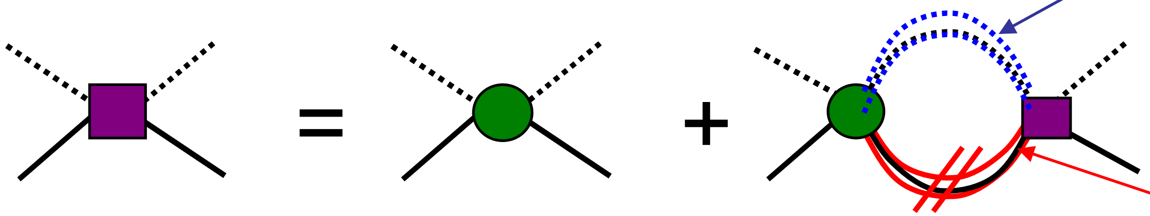
Free space



t-channel vector meson exchange (t->0 limit, HQSS..)

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

Medium

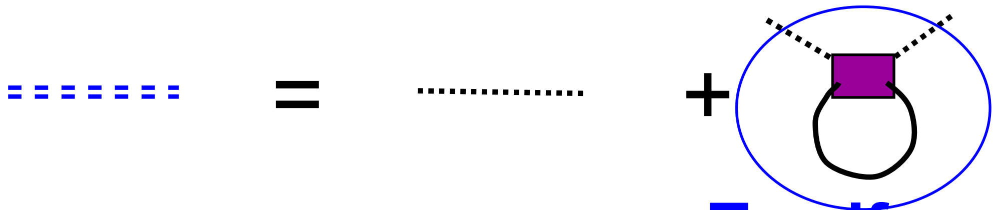


meson dressing

Pauli blocking and baryon dressing

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

Dressed meson:



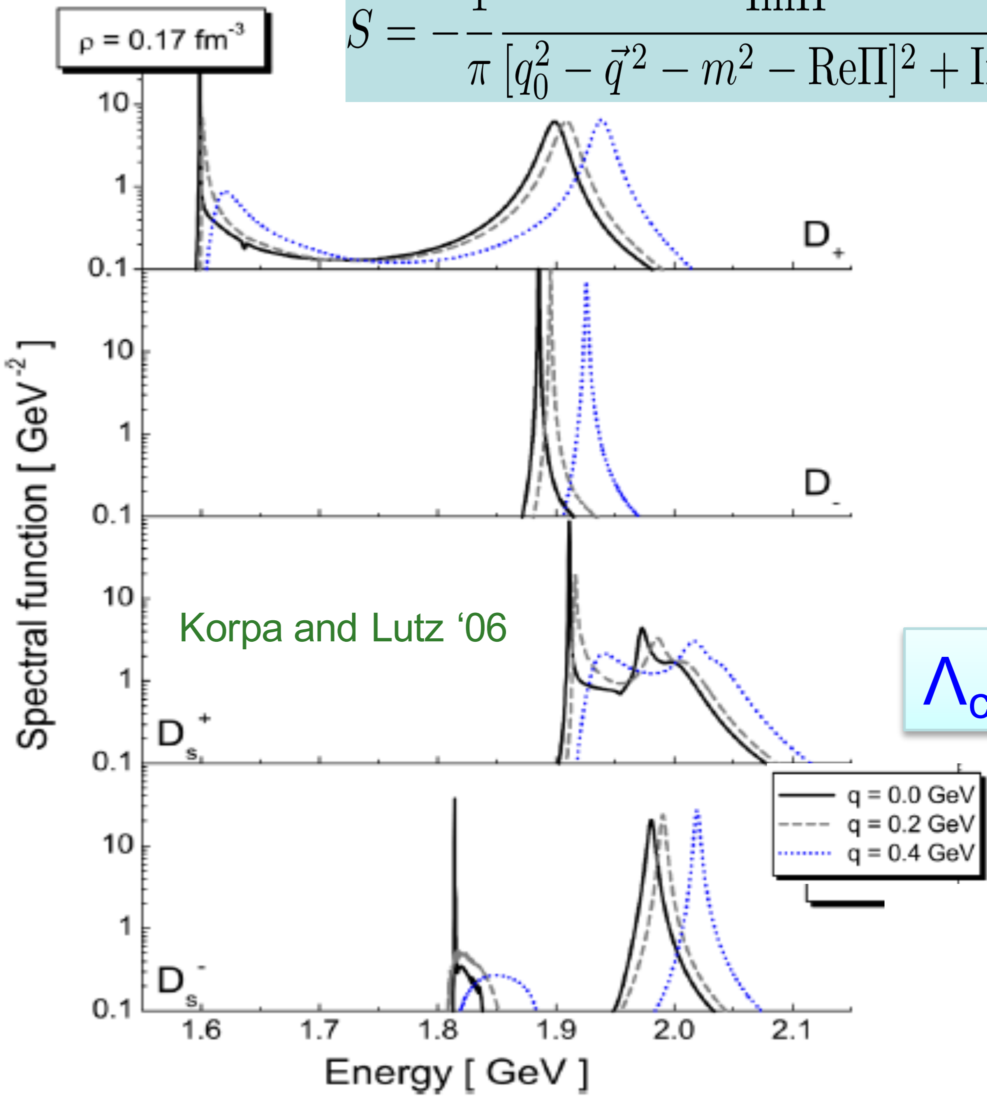
Π self-energy

unitarized theory in matter

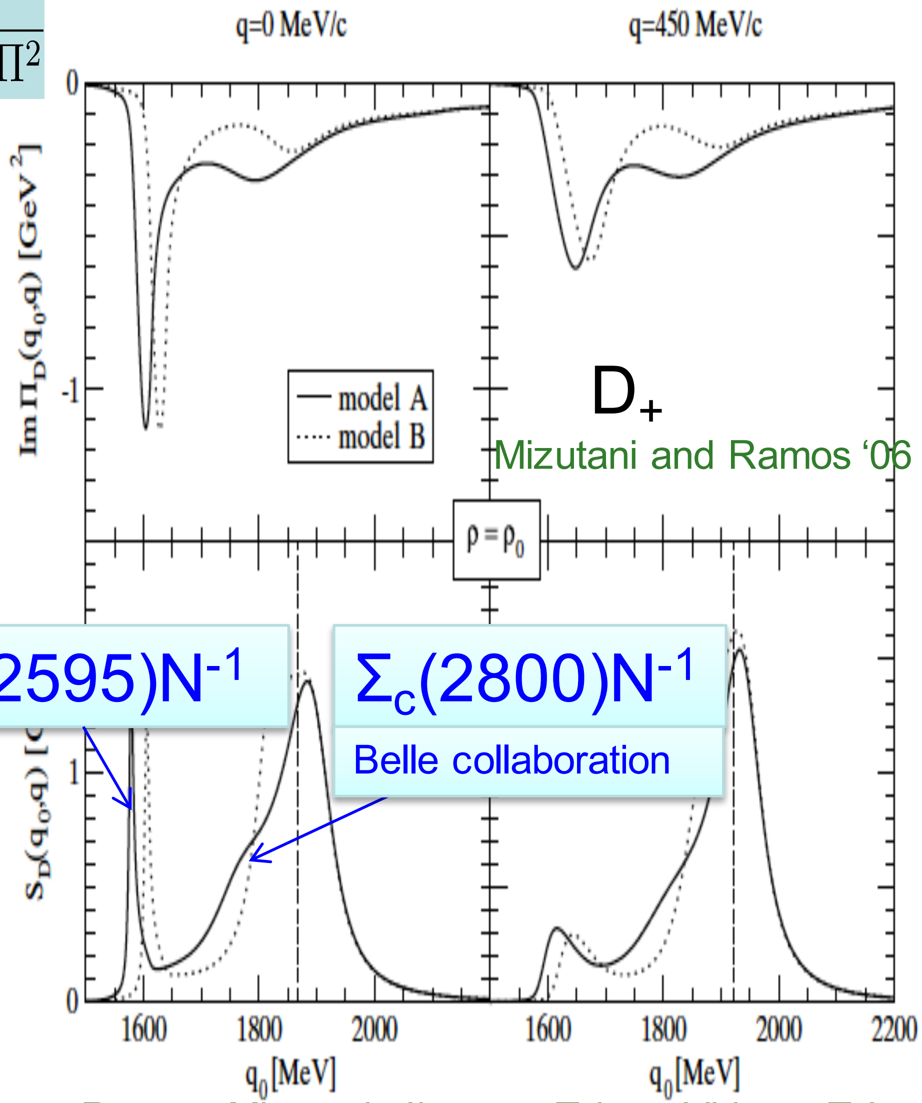
selfconsistent coupled-channel procedure

(bare interaction saturated by t-channel vector-meson exchange)

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



Lutz, Korpa, Hofmann..



Ramos, Mizutani, Jimenez-Tejero, Vidana, Tolos,..

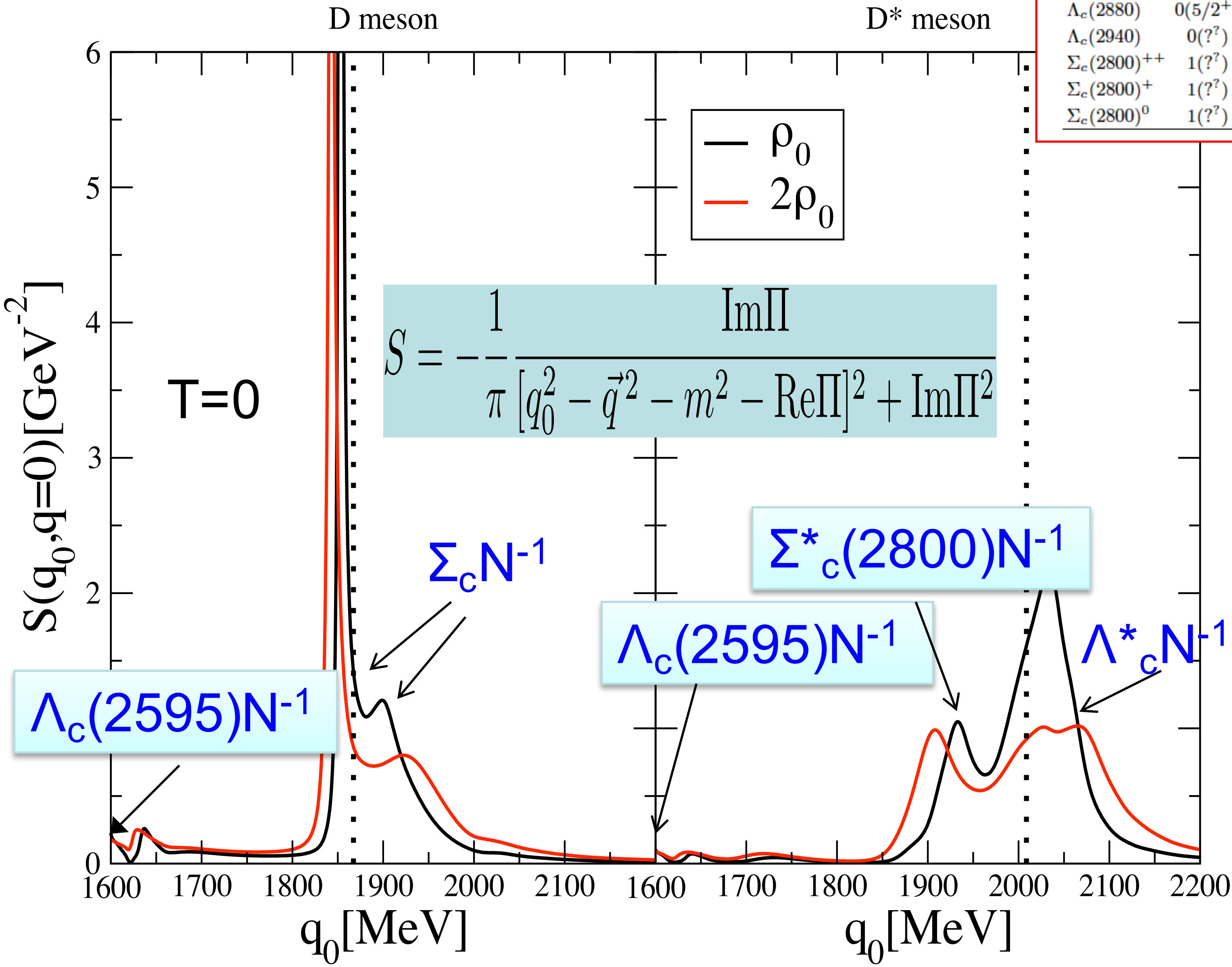
unitarized theory in matter:

selfconsistent coupled-channel procedure

(SU(6) x HQSS model)

PDG

Resonance	$I(J^P)$	Status	Mass [MeV]	Γ [MeV]
$\Lambda_c(2595)$	$0(1/2^-)$	***	2592.25 ± 0.28	2.6 ± 0.6
$\Lambda_c(2625)$	$0(3/2^-)$	***	2628.11 ± 0.19	< 0.97
$\Lambda_c(2765)$ or $\Sigma_c(2765)$	$?(?^?)$	*	2766.6 ± 2.4	50
$\Lambda_c(2880)$	$0(5/2^+)$	***	2881.53 ± 0.35	5.8 ± 1.1
$\Lambda_c(2940)$	$0(?^?)$	***	$2939.3 + 1.4 - 1.5$	$17 + 8 - 6$
$\Sigma_c(2800)^{++}$	$1(?^?)$	***	$2801 + 4 - 6$	$75 + 22 - 17$
$\Sigma_c(2800)^{+}$	$1(?^?)$	***	$2792 + 14 - 5$	$62 + 60 - 40$
$\Sigma_c(2800)^{0}$	$1(?^?)$	***	$2806 + 5 - 7$	$72 + 22 - 15$



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

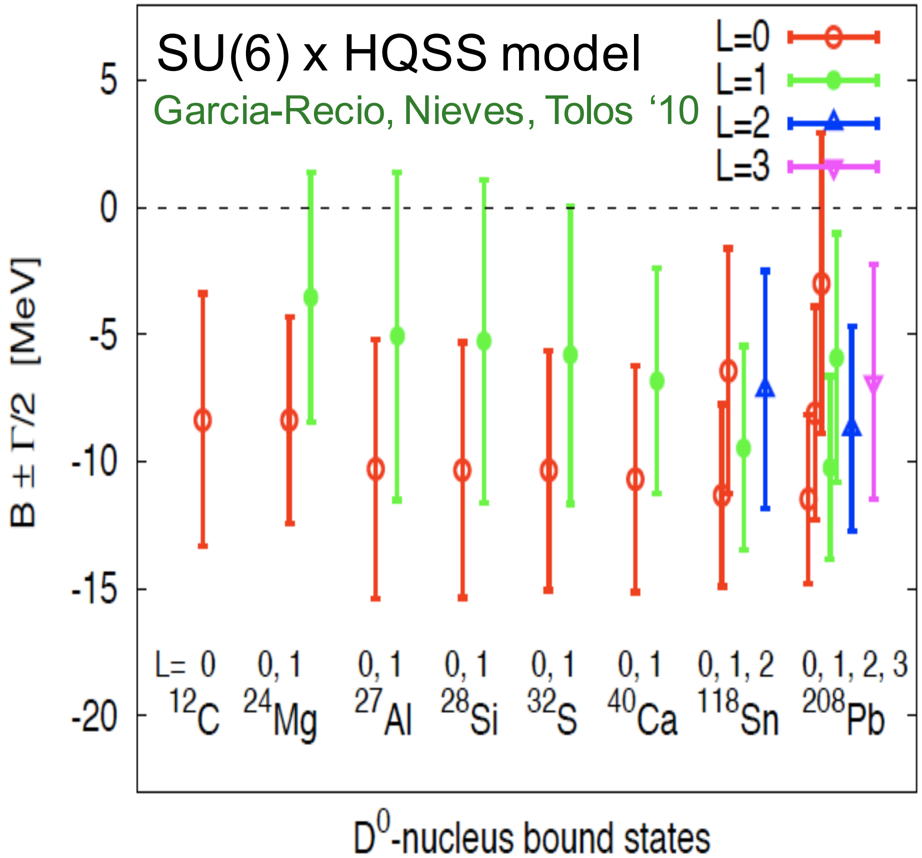
Simultaneous calculation of D and D* self-energies

Garcia-Recio et al '09
Tolos et al. '10;
Gamermann et al. '10
Garcia-Recio et al. '10
Garcia-Recio et al.'12
Romanets et al. '12
Garcia-Recio et al.' 13

D-mesic nuclei

Solving Schroedinger or Klein-Gordon equation with
- potential from QMC model
- potential from SU(6) x HQSS model
- potential from π exchange model with HQS

D^0 and D^+



- SU(6) x HQSS model: weakly bound D^0-nucleus states with important widths in contrast to previous QMC model

^{208}Pb

State	$D^0(V^q_\omega)$
$1s$	-96.2
$1p$	-93.0
$2s$	-88.5

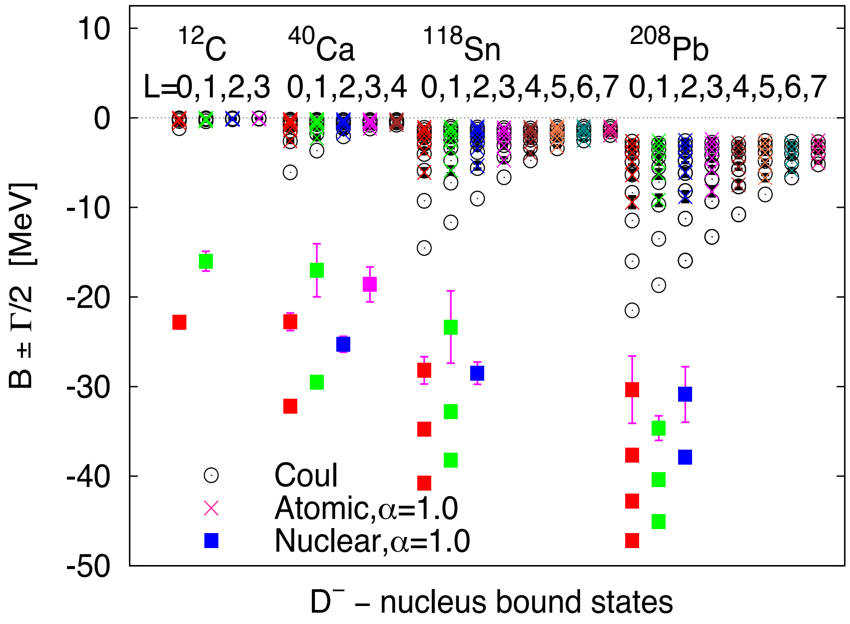
Tsushima et al. '99

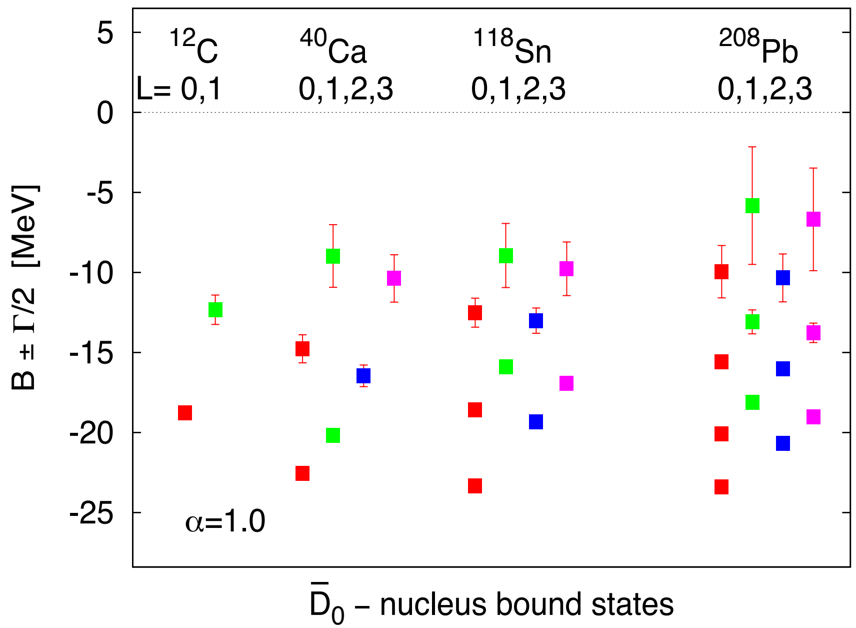
- SU(6) x HQSS model:
D^+ does not bind

D^- and $\bar{D}^0$

SU(6) x HQSS model:

Garcia-Recio, Nieves, Salcedo and Tolos '12





QMC model

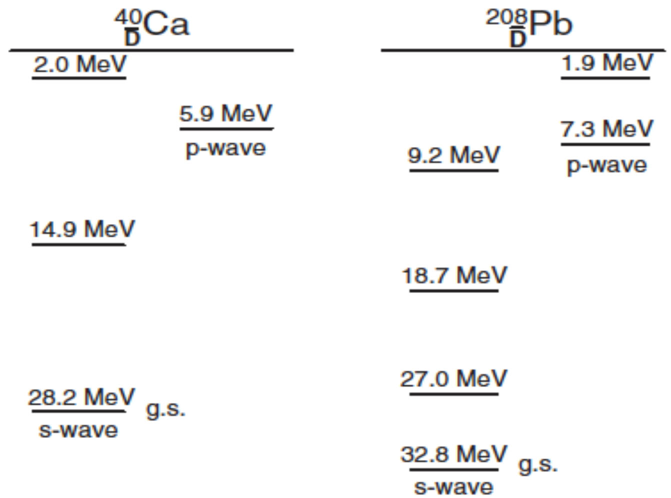
Tsushima, Lu, Thomas, Saito and Landau '99
Krein, Thomas and Tsushima '17

^{208}Pb

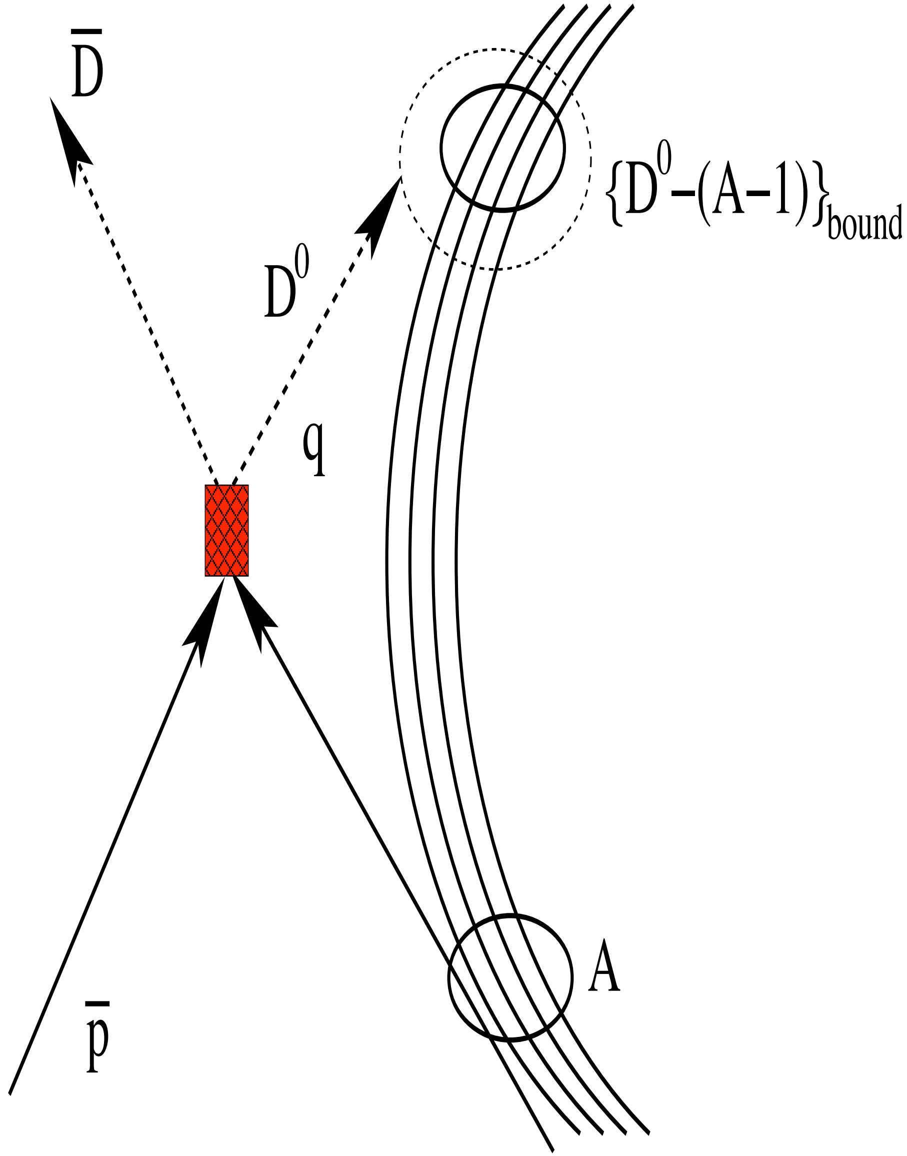
State	$D^-(\tilde{V}^q_\omega)$	$D^-(V^q_\omega)$	$D^-(V^q_\omega$, no Coulomb)	$\bar{D}^0(\tilde{V}^q_\omega)$	$\bar{D}^0(V^q_\omega)$
1s	−10.6	−35.2	−11.2	Unbound	−25.4
1p	−10.2	−32.1	−10.0	Unbound	−23.1
2s	−7.7	−30.0	−6.6	Unbound	−19.7

π exchange model with HQS

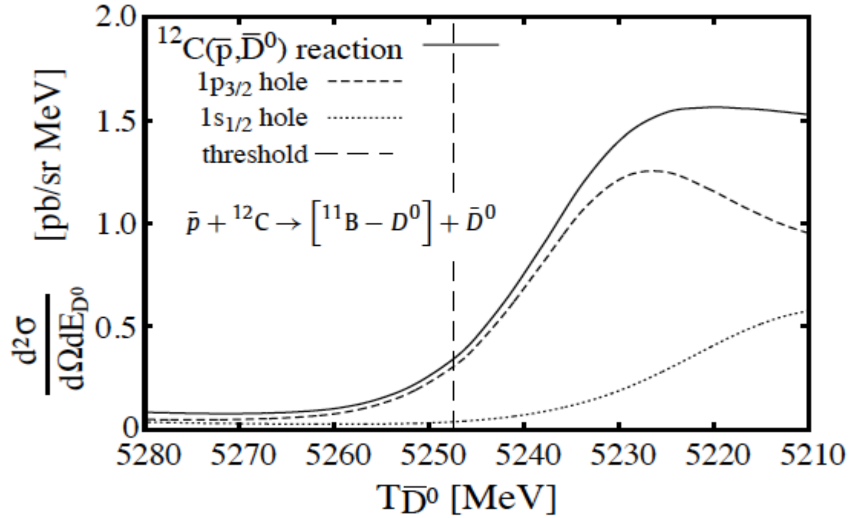
Yasui and Sudoh '13



Experimental observation is, though, a difficult task (PANDA, J-PARC?)

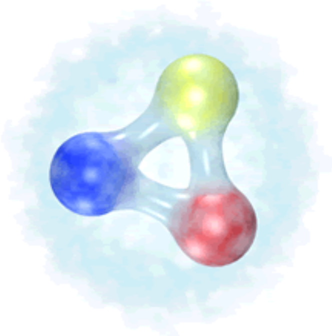


Yamagata-Sekihara, Garcia-Recio, Nieves, Salcedo and Tolos '16

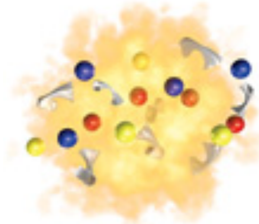


Large momentum transfer (about 1 GeV/c) makes any structure due to bound states not noticeable. Need of reactions with lower momentum transfer, such as

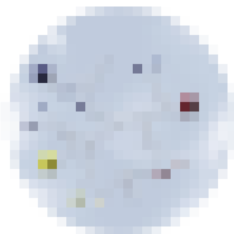
$$\bar{p} + p \rightarrow D^{*-} + D^+,$$
$$D^{*-} + A_Z \rightarrow \pi^0 + [A_Z - D^-]_b$$



present and future



- it is an exciting moment



- from light to heavy sector
- a lot of theoretical effort is needed
- but in close connection to experiments