# J-PARCにおける 原子核中のハドロン

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## our aim

- produce new hadron-nucleus systems
- investigate the properties    structure, hadron properties
- extrapolate the knowledge    dense nuclear matter (neutron star)

## hadron-nucleus system (new exotics)

mesons in nuclei（中間子原子核）

hadronic molecular states    etc.

(hadronic atoms)    ex. π atom, K atom, Ξ atom, ...

(hypernuclei)

## fundamental interactions

hadron spectroscopy, hadron structure

baryon resonance: **mesons excite nucleons in nuclei**

## ultimate goal

understanding of strong interactions of QCD

# Kaons in nuclei

one of the ultimate goals

$$\Sigma_K(E_K, \rho_p, \rho_n)$$

obtain self-energy as functions of c

kaon condensation in neutron star

Kaons are probably bound

properties of bound states g

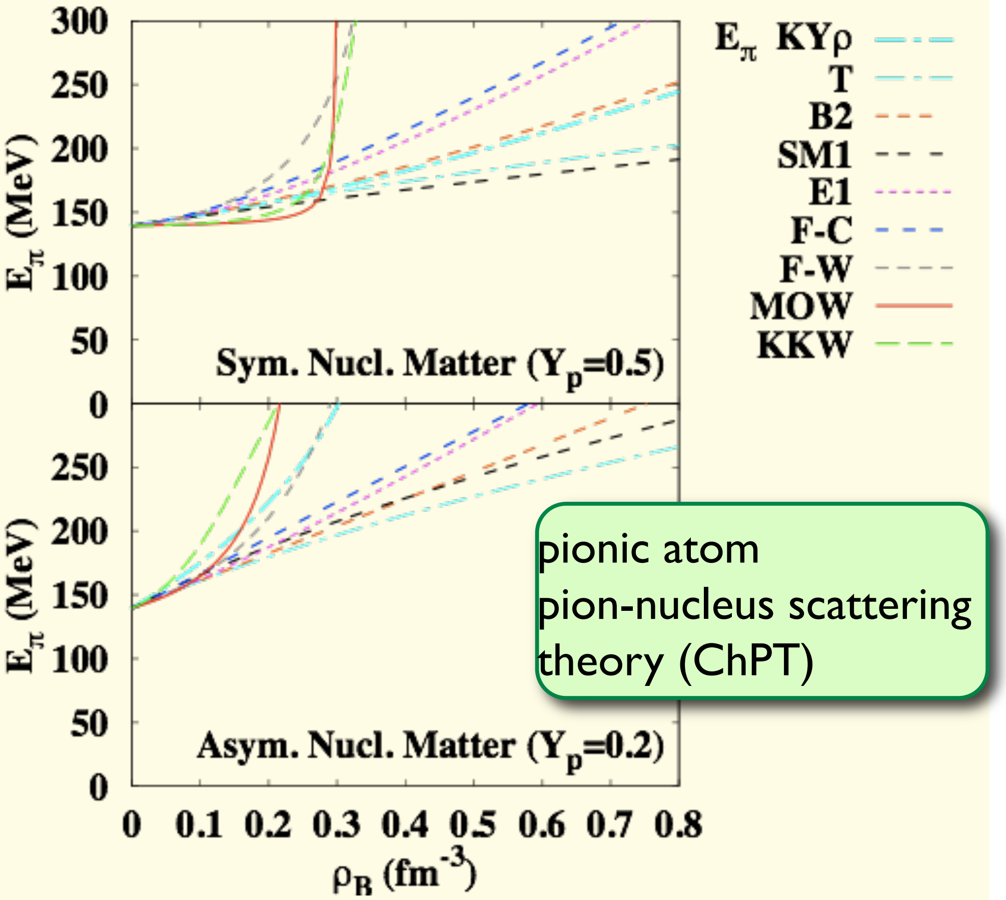
need peaks !!

a lot of subcomponents and

→ selective reactions fo

calculate whole structure of

**in medium $\pi^-$ mass**



pionic atom
pion-nucleus scattering
theory (ChPT)

Ohnishi, Jido, Sekihara, Tsubakihara, in preparation

# mesons in nuclei（中間子原子核）

## challenge of mesic nuclei

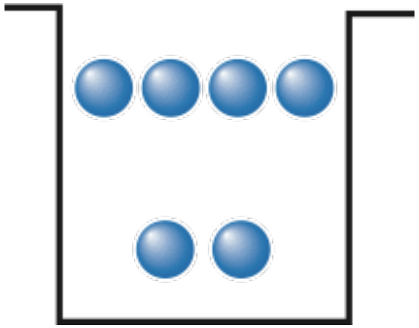
| | **mesic atom**<br>**(hypernuclei)** | **mesic nuclei** |
|---|---|---|
| **binding** | Coulomb assisted<br>(strong int.) | strong int. |
| **decay** | strong int.<br>(weak int.) | strong int. |
| **possible orbits** | surface or outside<br>(inside nucleus) | inside nucleus |
| **width** | keV 〜 1 MeV | several 10s MeV<br>couples to B* |
| **bound states** | well separated | **overlapped** |

# mesons in nuclei（中間子原子核）

## recoilless kinematics

selection rule for nucleon hole and meson states

$$s_N^{-1} \otimes s_m,\ p_N^{-1} \otimes p_m, \ldots$$



meson ground state is s-state

- creation of s-state hole costs energy
- nuclei with s-state hole are highly excited states
- large distortion effects

**as another possiblity**

two-nucleon pick-up reaction (π,d), (γ,d) etc.

J=0 with “shallow” two nucleon holes and meson

complications in theoretical calculations

# mesons in nuclei（中間子原子核） cf. hadronic atoms

**meson-nucleus systems governed by strong interactions**

issue: **bound or unbound ?** $K^{bar}N$: strong attraction

mesons

| | |
|---|---|
| **$K^{bar}$**, η, ω, η', Φ, J/Ψ, .... | narrow widths in vacuum |
| σ, ρ, K*, .... | wide widths in vacuum |
| π, K, ..... | repulsive |

bind and decay by strong interactions

**wide widths naturally expected** how wide ??

suppression of widths in deeply bound systems !?

**mesons excite nucleons in nuclei**

creation of baryon resonances in nuclei

meson - B*-hole couplings

**hadronic excitation of hypernuclei**

# $\phi$中間子原子核

カイラル対称性の部分的回復を strange quark で見る

φN 相互作用は U(3) 対称性では消える (OZI rule)

OZI rule の破れと $\langle N|\bar{s}s|N\rangle$

hadronic decay $\phi \to K\bar{K}$

核媒質効果の asymmetry

$K^{\text{bar}}N$ 引力

KN 斥力

# $\omega$中間子原子核

ωN と N(1520) $3/2^-$ との結合 ?!

# η'中間子原子核

Nagahiro, Hirenzaki, PRL97, 232503 (05)
Nagahiro, Takizawa, Hirenzaki, PRC74, 045203 (06)

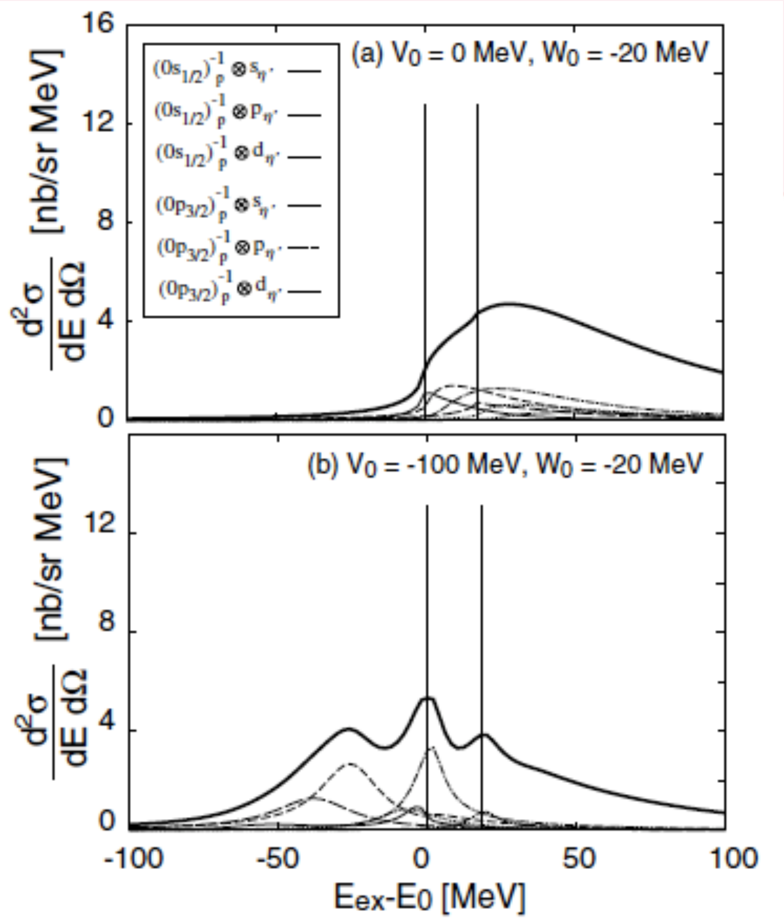
$U_A(1)$ 量子異常による重い質量

QCD における operator 関係式

カイラル対称性の自発的な破れを通して質量に反映

原子核中での質量変化

η-η' mixing



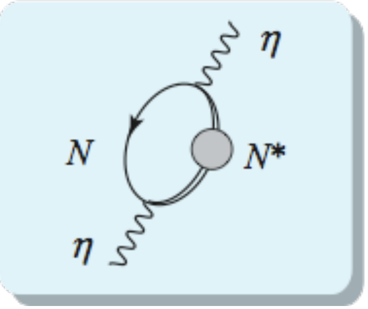
$^{12}\mathrm{C}(\gamma,p)$

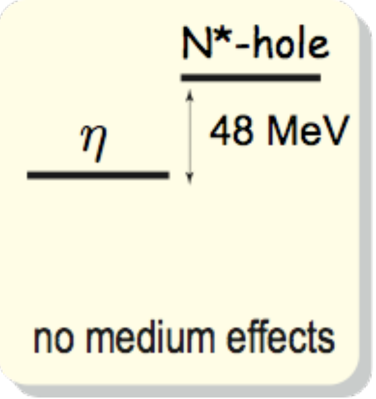
$E_\gamma$ = 3GeV

Nagahiro, Hirenzaki PRL97, 232503 (2005)

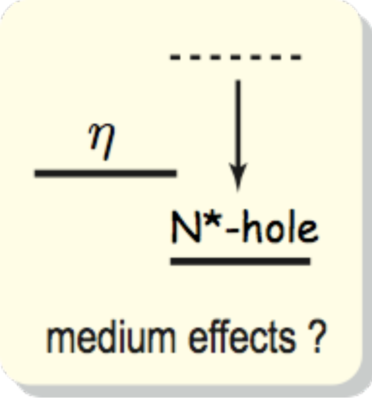
# $\eta$中間子原子核 (eta mesic nuclei)

- $\eta$N strongly couples to N(1535)
- level crossing of $\eta$ and N*-h modes

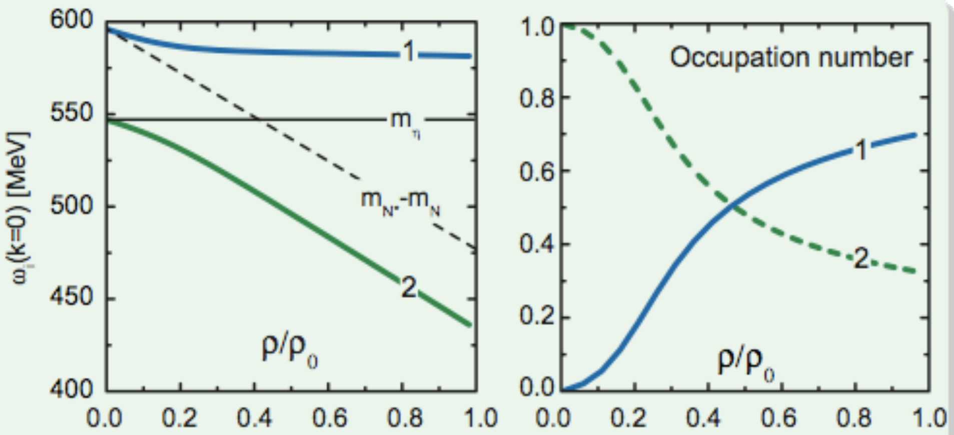




**Attractive**



**Repulsive**



$$G_\eta(\omega) = \sum_i \frac{Z_i}{\omega - \omega_i} \qquad Z_i = \left(1 - \left.\frac{\partial V_\eta(\omega)}{\partial \omega}\right|_{\omega=\omega_i}\right)^{-1}$$

- N(1535) is a candidate of chiral partner of N

Reduction of the mass difference of N and N*

Jido, Nagahiro, Hirenzaki, PRC66, 045202 ('02)
Nagahiro, Jido, Hirenzaki, PRC68, 035205 ('03), NPA761,92 ('05)
Jido, Kolomeitsev, Nagahiro, Hirenzaki, NPA accepted

# Spectral function of in-medium eta meson

Energy dependence

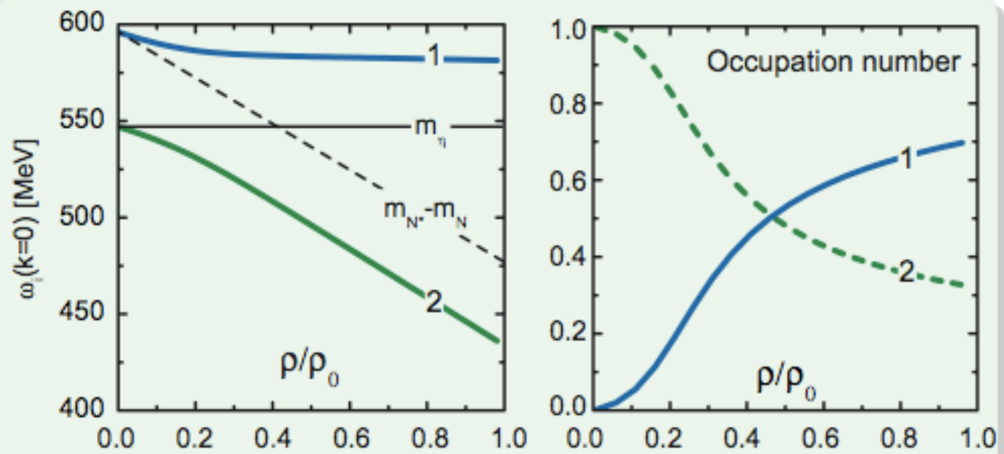
Infinite matter calc.

**Green function**

$$G_\eta(\omega) = \frac{1}{\omega - m_\eta - V_\eta(\omega)}$$

**Optical potential of $\eta$ in nucleus**

$$V_\eta(\omega) = \frac{g_\eta^2}{2\mu}\frac{\rho(r)}{w + m_N^*(\rho) - m_{N^*}^*(\rho) + i\Gamma_{N^*}(\omega;\rho)/2}$$

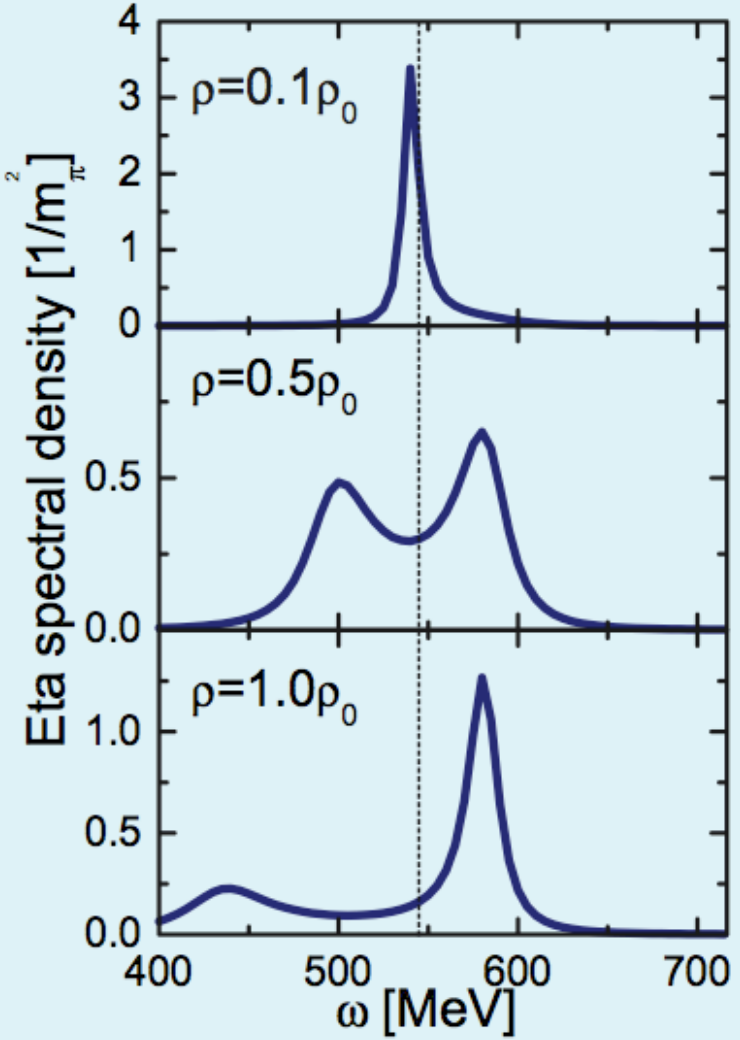


$$G_\eta(\omega) = \sum_i \frac{Z_i}{\omega - \omega_i}$$

$$Z_i = \left(1 - \frac{\partial V_\eta(\omega)}{\partial \omega}\Big|_{\omega=\omega_i}\right)^{-1}$$

**Spectral function**

$$S(\omega) = -\mathrm{Im}\, G_\eta(\omega)$$

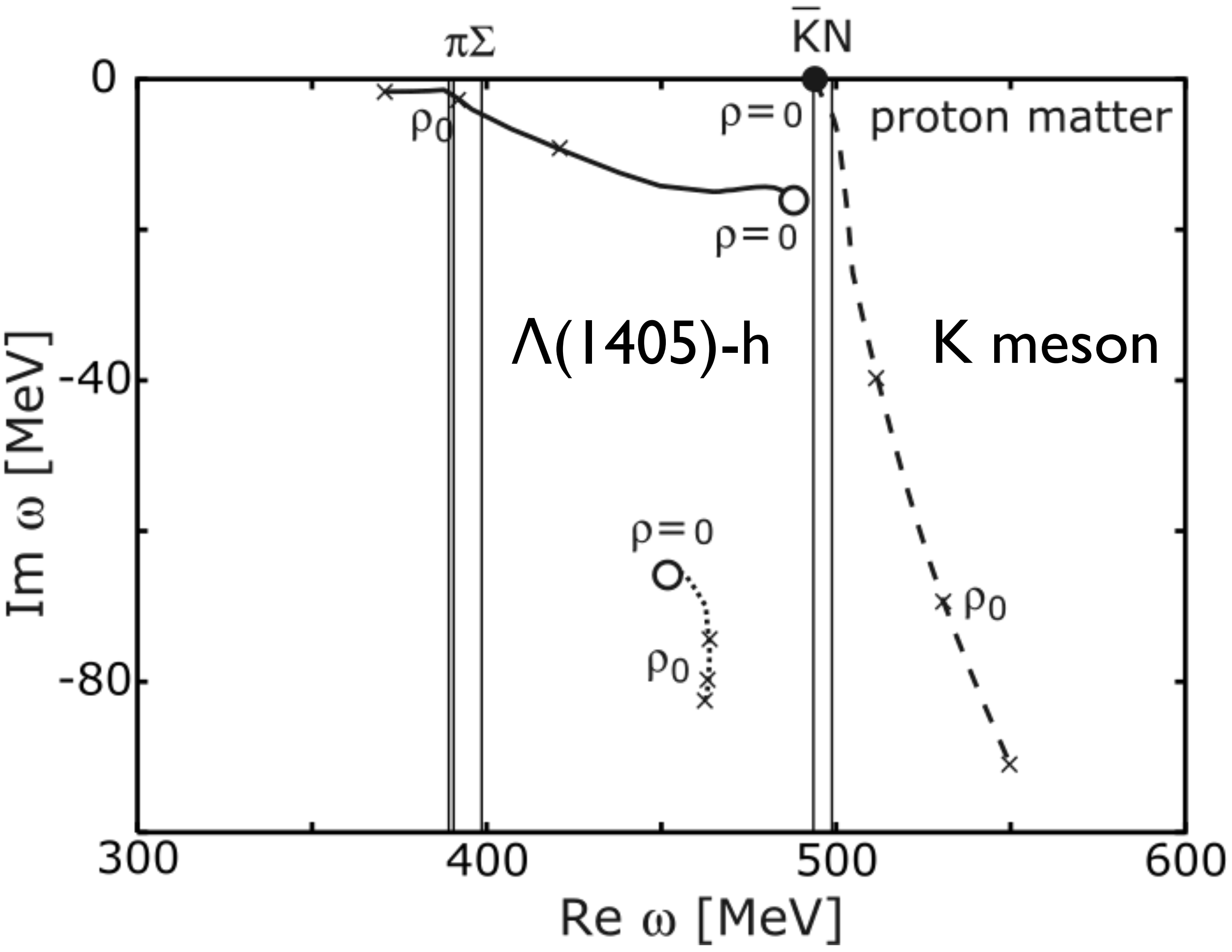


Jido, Nagahiro, Hirenzaki, PRC66, 045202 ('02)
Jido, Kolomeitsev, Nagahiro, Hirenzaki, NPA accepted

# K meson and Λ(1405)-h modes

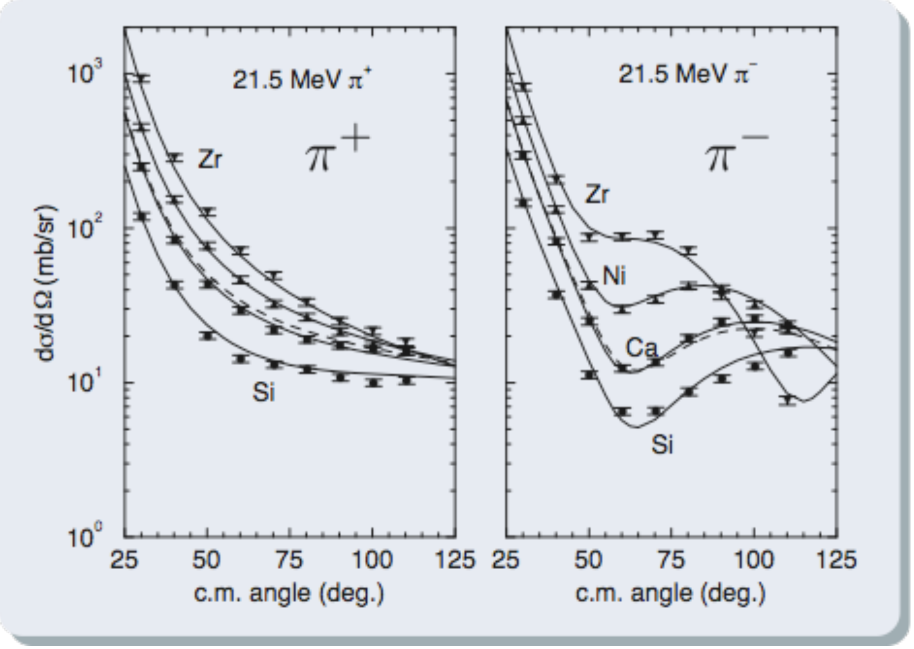
Yamagata, Jido, Nagahiro, Hirenzaki
in preparation

$$G(s) = \frac{Z}{s - m_K^2 + \rho T_{\bar{K}N}}$$



# 原子核中での $K^+$

- KN 相互作用 (Strong も EM も) は斥力
  - $K^+$-原子核弾性散乱
- KN より下には状態がない
  - cf. $K^{bar}N$ には Λ(1405) がいる
- 情報が clean !?
  - cf. π-原子核散乱
- 原子核中の $f_K$ や KNσ 項



# ハドロン励起状態

**hadron resonances : produced by strong interactions**

theory : many models based on different aspects

experiment : rich and precise data

It's ready to investigate details of the structure of hadron resonances from both sides

**properties in vacuum** : masses, widths and couplings

**mesons in nuclei** : meson excites nucleon

**dynamical aspect**

decaying resonance → large hadronic components

hadron dynamics is important

**symmetry aspect**

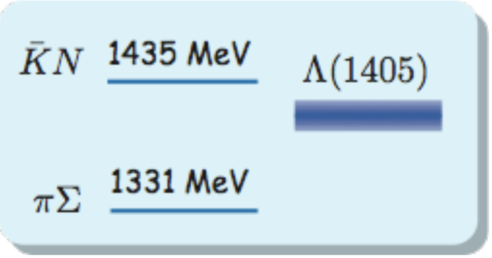
symmetry of quarks

chiral partners: N(1535) chiral partner of nucleon ??

# Double pole structute of Λ(1405)

DJ, Oller, Oset, Ramos, Meissner
NPA725, 181 ('03)

## Λ(1405) is a superposition of two states.



there are two attractive channels

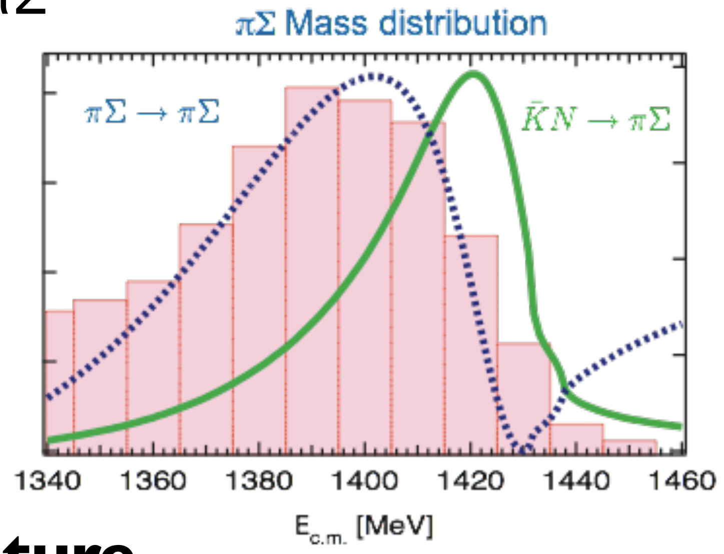
group theoretically SU(3) singlet and octet

physically $K^{bar}N$, πΣ

**Λ(1405)** below threshold of $\bar{K}N$

pole 1 : 1390 - 66i
- wider width
- strongly couples to $\pi\Sigma$ state

pole 2 : 1426 - 16i
- narrower width
- dominantly couples to $\bar{K}N$ state



## Implication of double pole structure

Λ(1405) spectrum is dependent on channels

Resonance position in $K^{bar}N$ channel ~1425 MeV with narrower width

not 1405 MeV

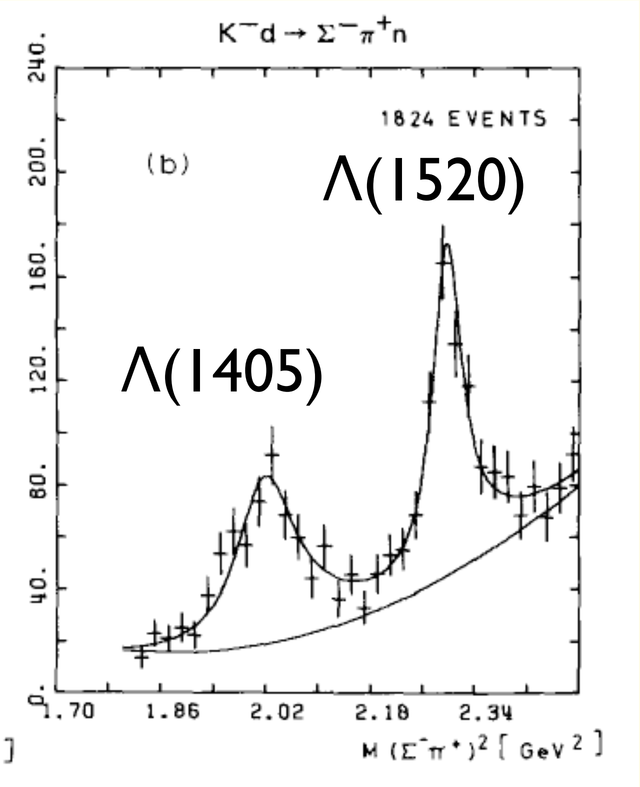
This 20 MeV difference is important for $K^{bar}N$ interactions

# Subthreshold properties of K$^{\text{bar}}$N

Λ(1405) spectra in K$^{\text{bar}}$N channel

$$\bar{K}N \to \Lambda(1405)$$

$$\boxed{K^- d \to \Lambda(1405) n}$$

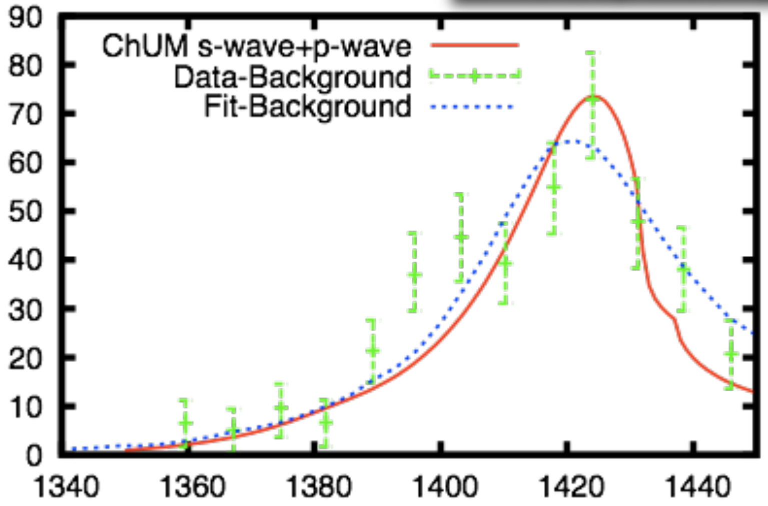


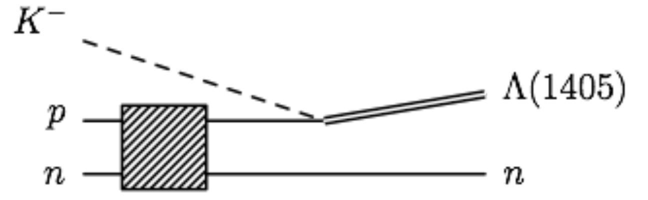
$$K^- d \to \pi^+ \Sigma^- n$$

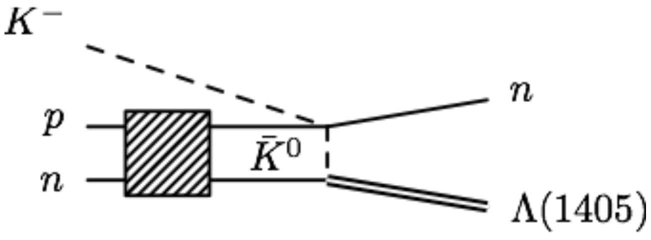
peak position 1420 MeV

NPB129,1,('77)    bubble chamber

Sekihara, DJ, Oset, in progress







# N(1535) のカイラル電荷

$g_A^{N^*} \sim g_{\pi N^* N^*}$

バリオンのカイラル対称性と密接に関連

$g_A^{N^*} > 0$ “naive” assignment — massless in χ restoration

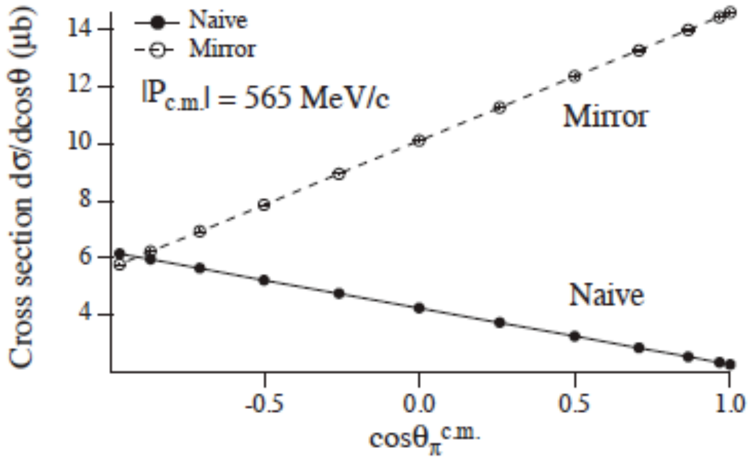
$g_A^{N^*} < 0$ “mirror” assignment — massive in χ restoration

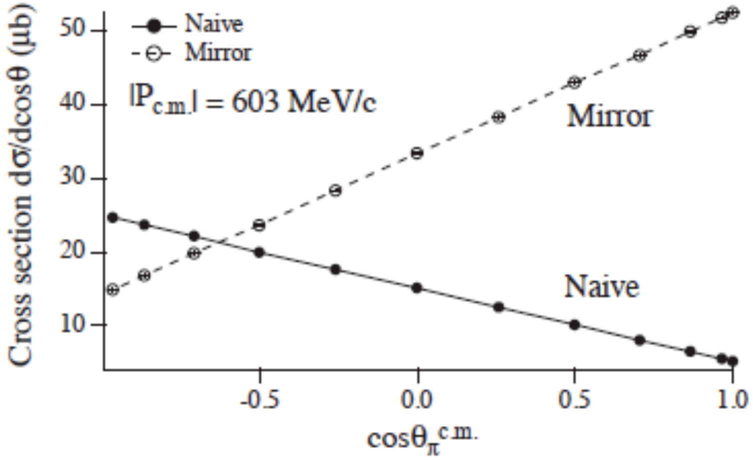
Lattice では、 $g_A^{N^*} \sim 0$

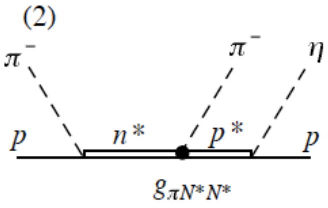
T.T. Takahashi, T. Kunihiro

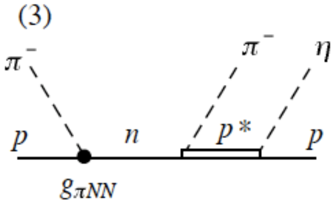
$$\pi^- p \rightarrow \pi^- \eta p$$

N(1535) dominant around threshold









Jido, Oka, Hosaka, PTP106, 823 (’01)

# ハドロン励起状態の大きさ

励起状態の構造

クォーク自由度 v.s. ハドロン自由度

ハドロン分子状態 ~ 原子核中の核子間距離 (~1 fm)

異なる核媒質効果

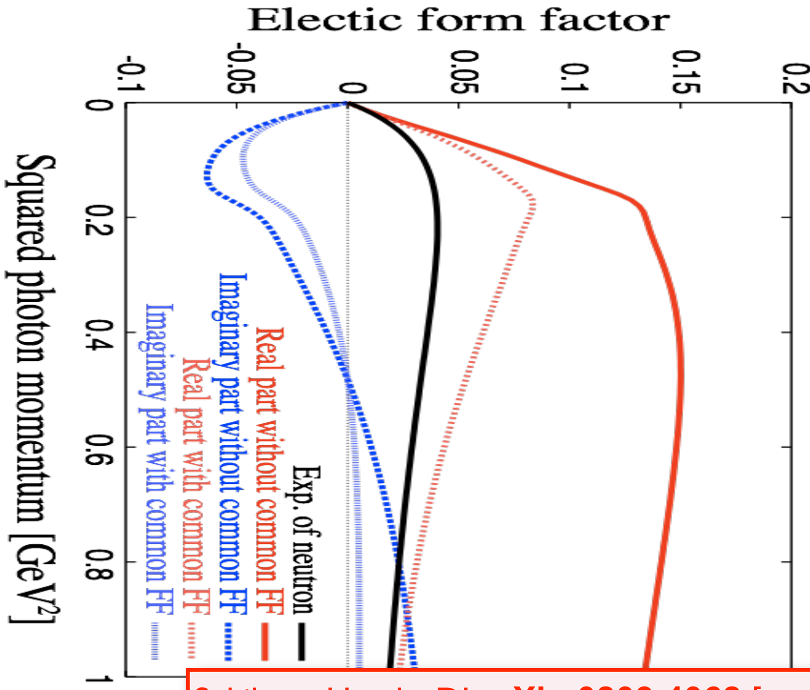
Λ(1405)の荷電半径
(diagonal form factor)

$K^{bar}N$　negative

πΣ(I=0) almost zero

transition form factor

energy dependence in production



Sekihara, Hyodo, DJ **arXiv:0803.4068** [nucl-th];
in priparation

# hadronic molecular

**新しいハドロン励起状態**

K中間子が特別な役割

N* as KKbarN quasibound state

Ξ* as KKbarN quasibound state

main decay modes: three-body decay

**Λ(1405) への doorway**

Y. Kanada-En'yo, DJ, PRC78,025212 (08).
DJ, Y. Kanada-En'yo, **arXiv:0806.3601**, PRC in press

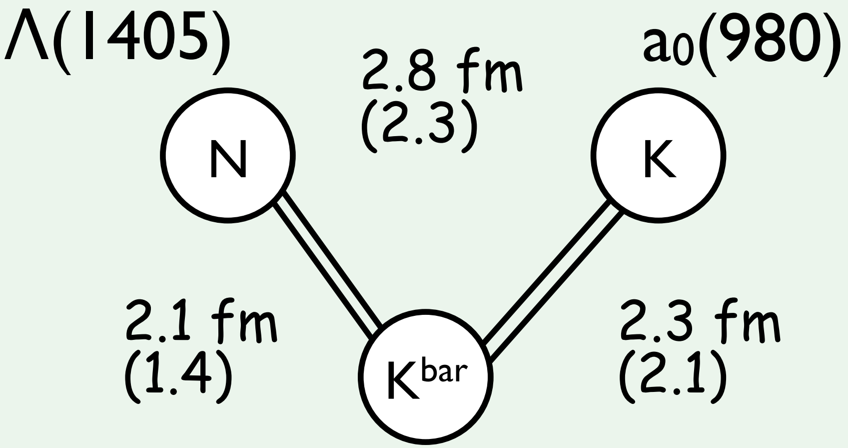
**N* around 1900 MeV** 20~40 MeV bound, 90~100 MeV width

*spacial structure*

hadron-hadron distances are comparable with nucleon-nucleon distances in nuclei

r.m.s radius (1.7 fm) is larger than that of $^4$He (1.4 fm)

mean hadron density: 0.07 hadrons/(fm$^3$)



## Connection to QCD

establish in-medium effective theory of QCD

in medium chiral perturbation theory

- medium modifications of LEC's    LEC = low energy constant
- fpi, fK, sigma term etc.

give connections to universal parameters

**exact sum rule** in chiral limit

DJ, Hatsuda, Kunihiro, **arXiv:0805.4453** [nucl-th]

$$\sum_{\alpha} \mathrm{Re}\left[(N_{\alpha}^{*} + F_{\alpha}^{*}) Z_{\alpha}^{*1/2}\right] = -\langle \bar{q} q \rangle^{*} \ .$$

low energy theorem

all zero modes contribute to in-medium quark condensate.

# Summary

**our aim**

- produce new hadron-nucleus systems
- investigate the properties
- extrapolate the knowledge

**mesons in nuclei ⇔ baryon resonance in nuclei**

B* hypernuclei

complex but interesting systems !!

a lot of things can be learnt

**challenges**

observe bound states !! wide widths and many subcomponents

calculate spectra in detail !!

necessary to establish in-medium effective theory

to connect observation to QCD

η

- mesons in nuclei

opening new states    experimental feasibility

- interests of hadrons in nuclear medium

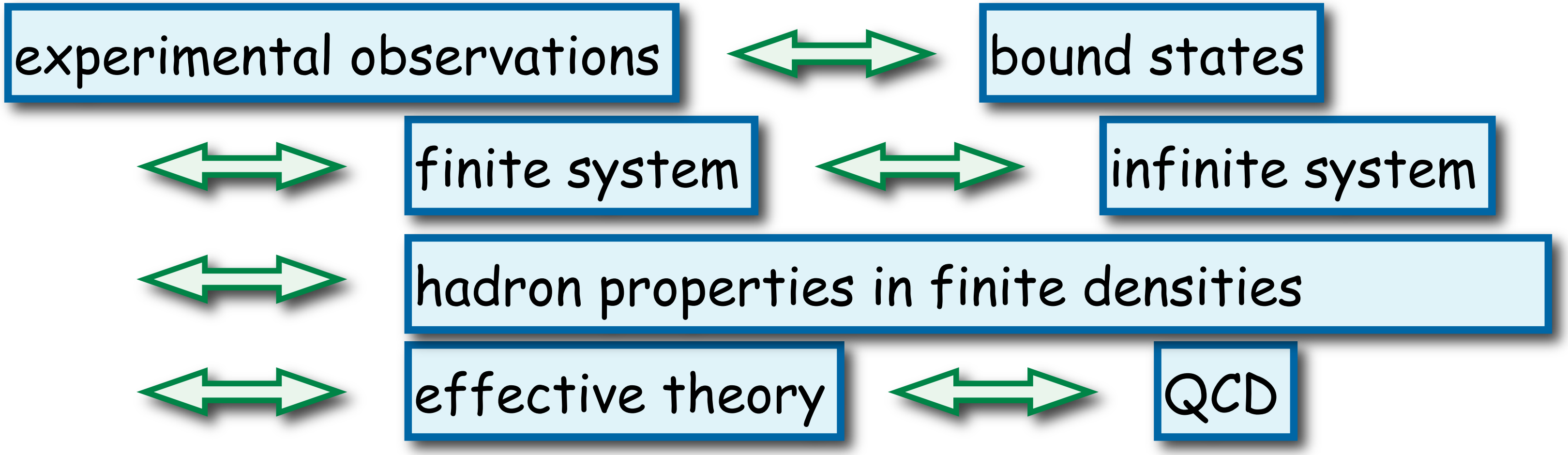
in-medium dynamics of hadron

properties of hadron, bound states in nuclei

modification of nuclear structure

partial restoration of chiral symmetry    universal properties

high density physics, ex. neutron star



experimental observations ⟺ bound states

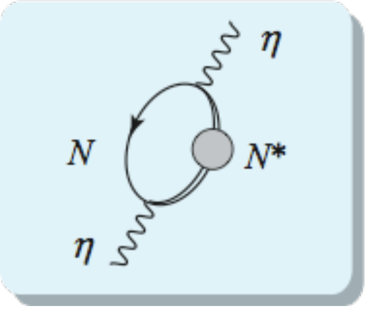
⟺ finite system ⟺ infinite system

⟺ hadron properties in finite densities

⟺ effective theory ⟺ QCD

# $\eta$ 中間子原子核 (eta mesic nuclei)

chiral doublet model と chiral unitary model の違いの詳細



どちらも N*-hole 模型

N* の取り扱い（picture）が異なる

chiral doublet model

N と N* が chiral doublet

N と N* の質量差が減少 → level crossing

chiral unitary model

N* : dynamically generated resonance

KΣ channel が重要 → Pauli blocking effect が小さい

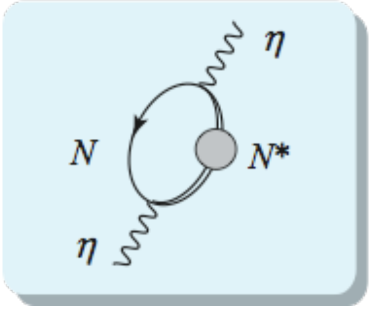
Jido, Nagahiro, Hirenzaki, PRC66, 045202 ('02)

# Optical potential of η in nucleus

## Assumption

1) N* dominance: Consider only N*-hole excitation.
2) s-wave coupling for $\eta$ NN*
3) $\eta$ at rest in nucleus due to the recoilless condition

**N*-hole excitation**



## Optical potential of $\eta$ in nucleus

$$V_\eta(\omega) = \frac{g_\eta^2 \, \rho(r)}{2\mu \boxed{w + m_N^*(\rho) - m_{N^*}^*(\rho)} + i\Gamma_{N^*}(\omega;\rho)/2}$$

| | |
|---|---|
| $g_\eta$ | ηNN* coupling |
| $\mu$ | η-nucleus reduced mass |
| $w$ | η energy |

Real part of optical potential depends on eta energy and mass difference of N and N*.

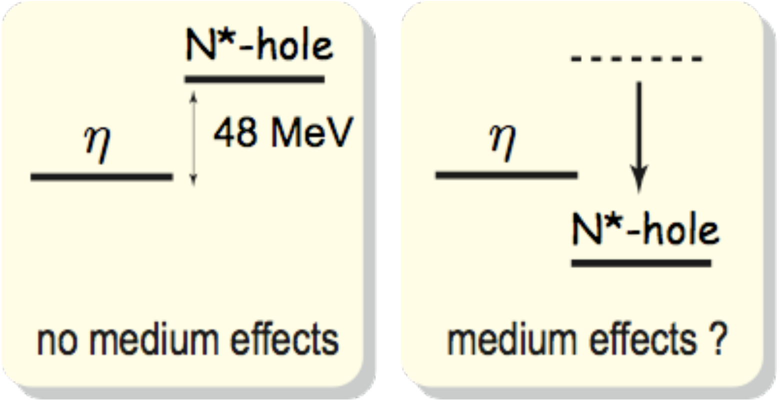
We have seen reduction of N-N* mass difference in nuclear medium in chiral doublet model.

$\omega + m_N^* - m_{N^*}^* > 0$ attraction

$\omega + m_N^* - m_{N^*}^* < 0$ repulsion

**Density dependence**

**Energy dependence**



**level crossing**

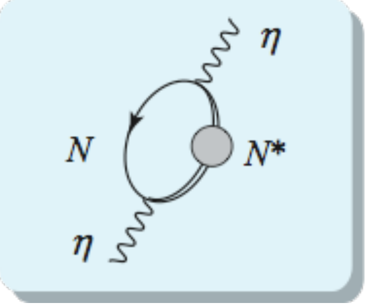
Jido, Nagahiro, Hirenzaki, PRC66, 045202 ('02)

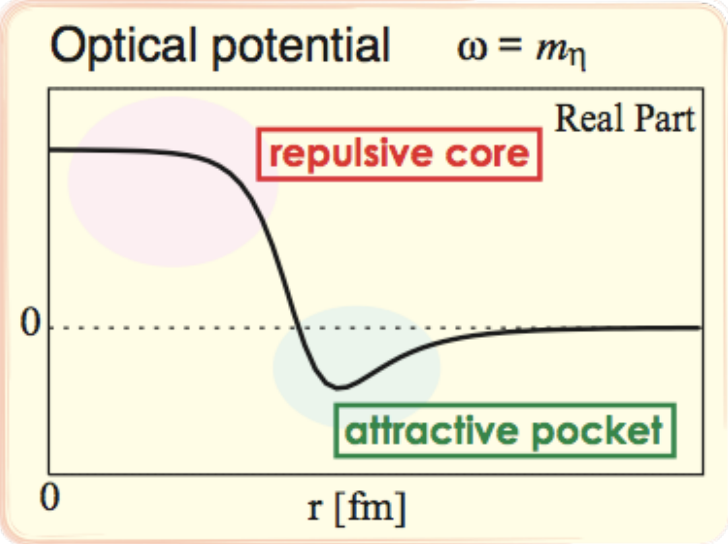
# Optical potential of η in nucleus

**Density dependence** fixing energy at $\omega = m_\eta$

**N(1535)* dominance**

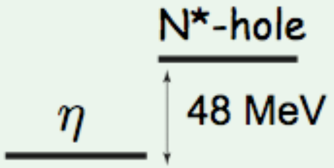
**N*-hole excitation**





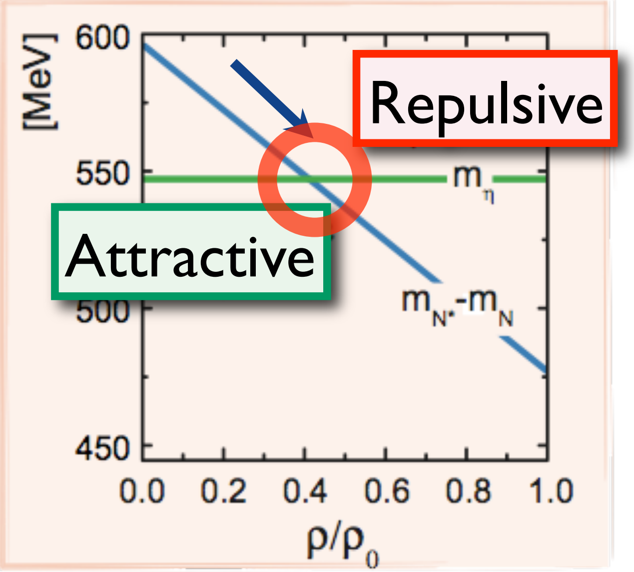
- no strong medium modification for the masses of N and N*

**Attractive**



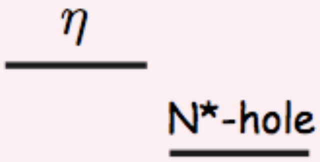
Reduction of mass difference of N and N*

**Level crossing** between eta and N*-hole modes



- sufficient reduction of the mass difference of N and N*

**Repulsive**



Jido, Kolomeitsev, Nagahiro, Hirenzaki, NPA accepted

# Green function of in-medium eta meson

Energy dependence

potential strongly depends on energy

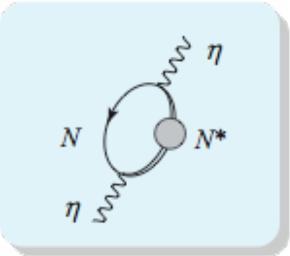
→ bound states calculated in self-consistent way

**Green function**

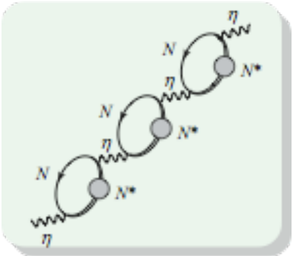
$$G_\eta(\omega) = \frac{1}{\omega - m_\eta - V_\eta(\omega)}$$

propagation of modes as poles

pole position: in-medium “mass”



Self-energy



Green function

**Two modes of propagation**

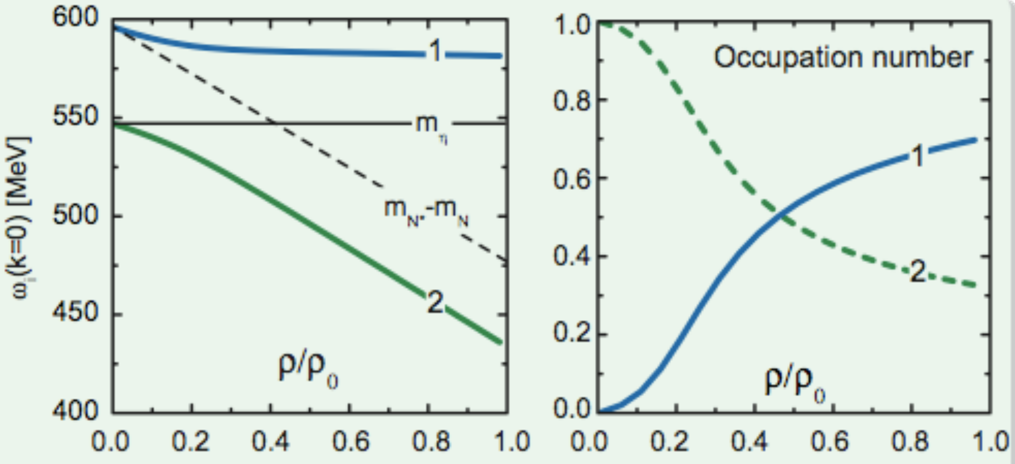
Eta meson mode

N*–hole mode

couple in nuclear medium

change places

if level crossing takes place



$$G_\eta(\omega) = \sum_i \frac{Z_i}{\omega - \omega_i} \qquad Z_i = \left(1 - \left.\frac{\partial V_\eta(\omega)}{\partial \omega}\right|_{\omega=\omega_i}\right)^{-1}$$

Jido, Kolomeitsev, Nagahiro, Hirenzaki, NPA accepted

# Spectral function of in-medium eta meson

Energy dependence

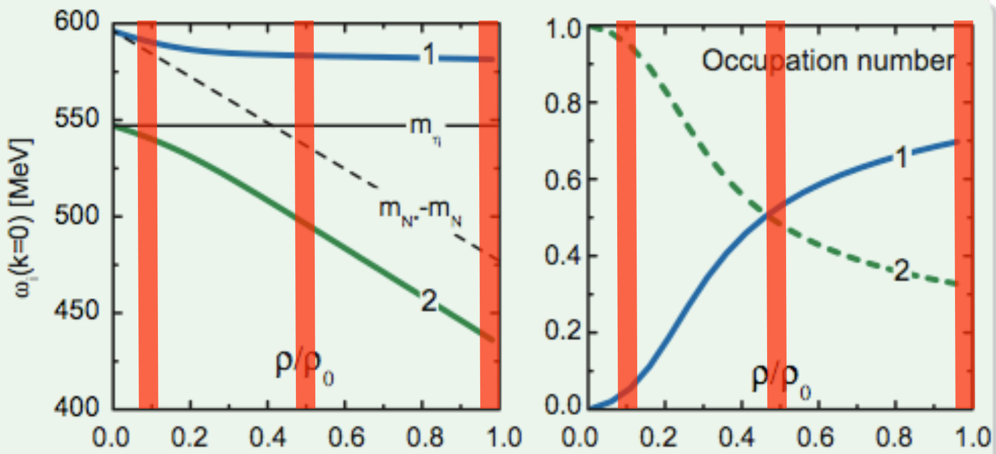
Infinite matter calc.

**Green function**

$$G_\eta(\omega) = \frac{1}{\omega - m_\eta - V_\eta(\omega)}$$

**Optical potential of $\eta$ in nucleus**

$$V_\eta(\omega) = \frac{g_\eta^2}{2\mu} \frac{\rho(r)}{w + m_N^*(\rho) - m_{N^*}^*(\rho) + i\Gamma_{N^*}(\omega;\rho)/2}$$

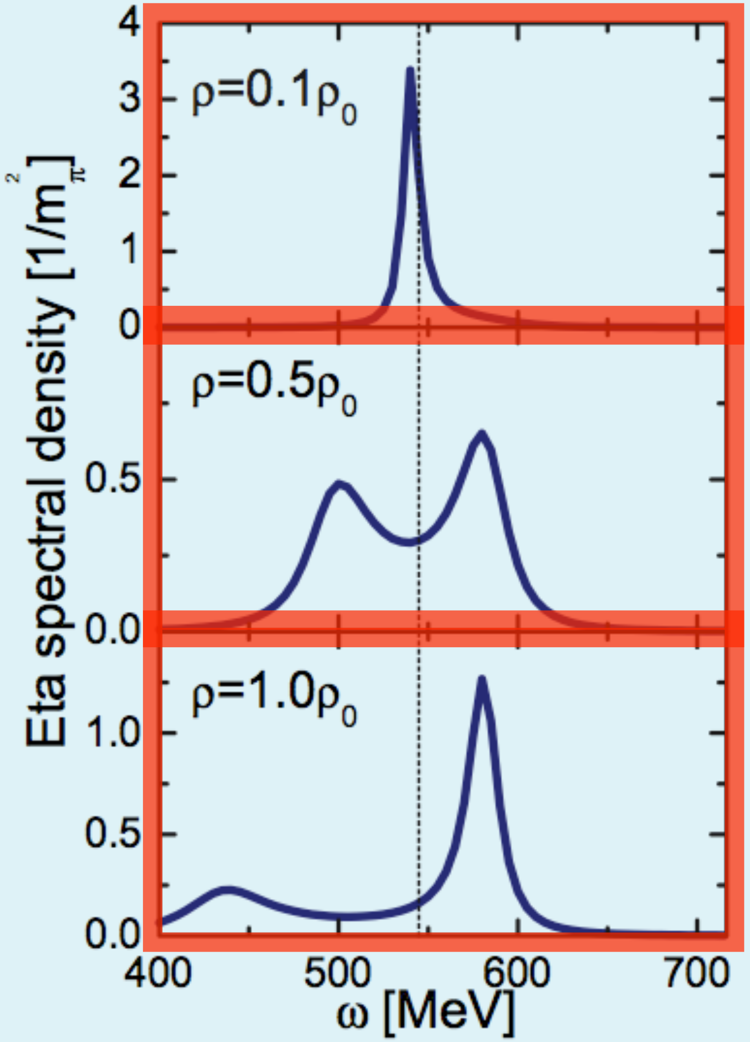


$$G_\eta(\omega) = \sum_i \frac{Z_i}{\omega - \omega_i}$$

$$Z_i = \left(1 - \frac{\partial V_\eta(\omega)}{\partial \omega}\bigg|_{\omega=\omega_i}\right)^{-1}$$

**Spectral function**

$$S(\omega) = -\mathrm{Im}\, G_\eta(\omega)$$



# What is hadronic molecular state ?

- *system of multiple hadrons described by hadron dynamics*

  possible constituents are ground states hadrons

  octet baryons: N, Λ, Σ, Ξ     octet meson: π, K, η

ex. Λ(1405)
as $K^{bar}N$ QBS

- *constituents keep their identity*

  typical binding energy ~ 10-20 MeV     weakly bound system

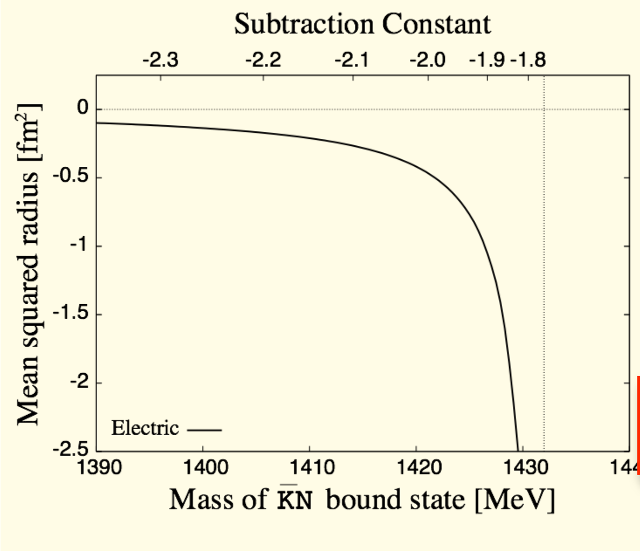
  decay width ~ 50 MeV (strong interactions)     **quasi-bound state**

- *spatially extended (large size)*

  typically more than 1 fm

- *softer form factors*

  strong energy dependence
  in production



**charge radius**
of Λ(1405) as
$K^{bar}N$ bound state

Sekihara, Hyodo, DJ
**arXiv:0803.4068** [nucl-th]

**quark degrees of freedom may be less important**

# K meson in Λ(1405)

small binding energy ~ 10-30 MeV

- **heavy particle** ~ half of nucleon mass
  - non-relativisitc treatment
    - cf. pion $m_\pi \approx 140\ \mathrm{MeV}$

isospin averaged mass

$$\begin{aligned} m_K &= 495.7\ \mathrm{MeV} \\ m_N &= 938.9\ \mathrm{MeV} \end{aligned}$$

- **Nambu-Goldstone boson**
  - strong s-wave attraction in $K^{\mathrm{bar}}N$
    - chiral effective theory momentum expansion
    - s-wave int. proportional to K energy

**Kaons are different from pions** in the energies of our interest !!

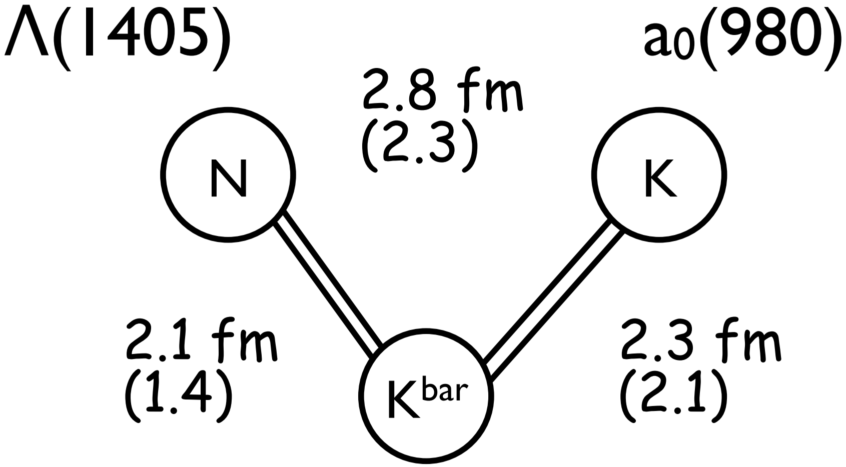
# **Result $\mathrm{KK}^{\mathrm{bar}}\mathrm{N}$** N* around 1900 MeV

*spacial structure*

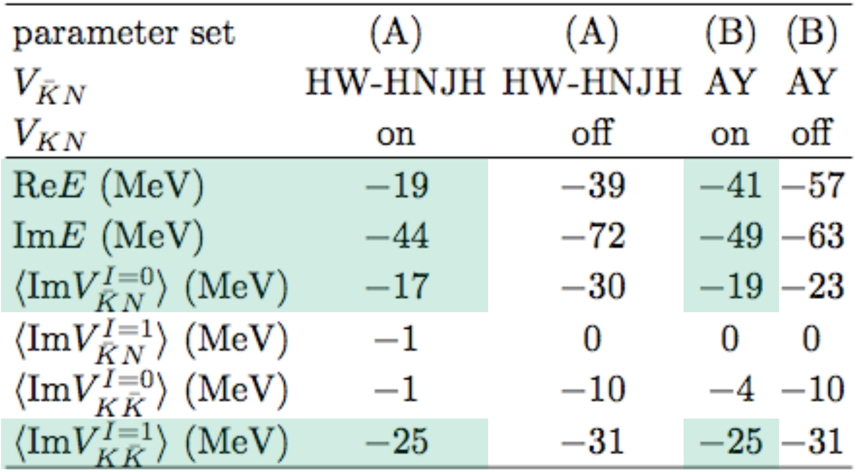
hadron-hadron distances are comparable with nucleon-nucleon distances in nuclei

r.m.s radius (1.7 fm) is larger than that of $^{4}$He (1.4 fm)

mean hadron density: 0.07 hadrons/(fm$^{3}$)

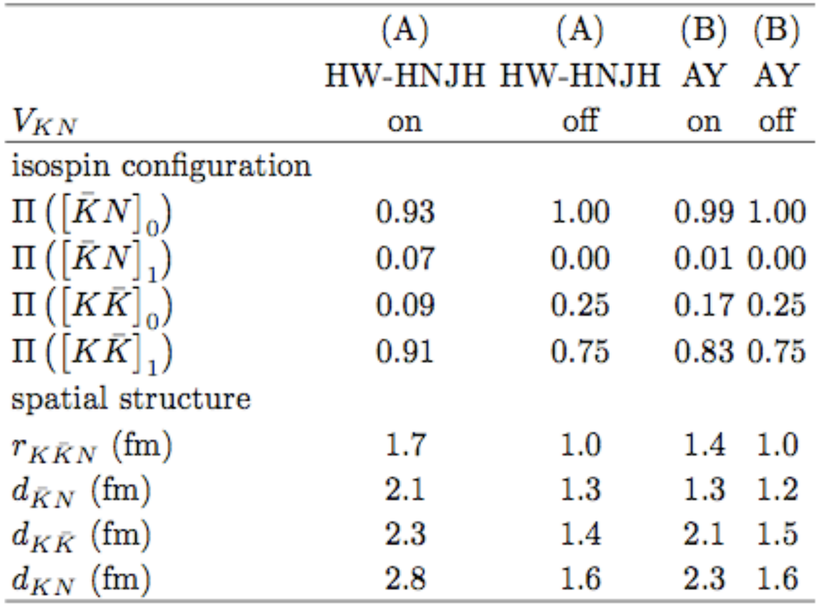


KN repulsion important



| parameter set | (A) | (A) | (B) | (B) |
|---|---|---|---|---|
| $V_{\bar{K}N}$ | HW-HNJH | HW-HNJH | AY | AY |
| $V_{KN}$ | on | off | on | off |
| Re$E$ (MeV) | −19 | −39 | −41 | −57 |
| Im$E$ (MeV) | −44 | −72 | −49 | −63 |
| $\langle \mathrm{Im}V^{I=0}_{\bar{K}N}\rangle$ (MeV) | −17 | −30 | −19 | −23 |
| $\langle \mathrm{Im}V^{I=1}_{\bar{K}N}\rangle$ (MeV) | −1 | 0 | 0 | 0 |
| $\langle \mathrm{Im}V^{I=0}_{K\bar{K}}\rangle$ (MeV) | −1 | −10 | −4 | −10 |
| $\langle \mathrm{Im}V^{I=1}_{K\bar{K}}\rangle$ (MeV) | −25 | −31 | −25 | −31 |

threshold of $\mathrm{KK}^{\mathrm{bar}}\mathrm{N}$ 1930 MeV



| | (A) | (A) | (B) | (B) |
|---|---|---|---|---|
| | HW-HNJH | HW-HNJH | AY | AY |
| $V_{KN}$ | on | off | on | off |
| isospin configuration | | | | |
| $\Pi\left([\bar{K}N]_0\right)$ | 0.93 | 1.00 | 0.99 | 1.00 |
| $\Pi\left([\bar{K}N]_1\right)$ | 0.07 | 0.00 | 0.01 | 0.00 |
| $\Pi\left([K\bar{K}]_0\right)$ | 0.09 | 0.25 | 0.17 | 0.25 |
| $\Pi\left([K\bar{K}]_1\right)$ | 0.91 | 0.75 | 0.83 | 0.75 |
| spatial structure | | | | |
| $r_{K\bar{K}N}$ (fm) | 1.7 | 1.0 | 1.4 | 1.0 |
| $d_{\bar{K}N}$ (fm) | 2.1 | 1.3 | 1.3 | 1.2 |
| $d_{K\bar{K}}$ (fm) | 2.3 | 1.4 | 2.1 | 1.5 |
| $d_{KN}$ (fm) | 2.8 | 1.6 | 2.3 | 1.6 |

# $K\bar{K}N$ system with $I=1/2$, $J^P=1/2^+$ (N*)

Interactions in $KK^{bar}N$ system

| | | I=0 | I=1 | threshold |
|---|---|---|---|---|
| $\bar{K}N$ | attraction | $\Lambda(1405)$ | weak attraction | 1434.6 MeV |
| $K\bar{K}$ | | $f_0(980)$ | $a_0(980)$ | 991.4 MeV |
| $KN$ | repulsion | very week | strong repulsion | 1434.6 MeV |

$\Lambda(1405)$, $f_0(980)$ and $a_0(980)$ are assumed to be quasi-bound states

naturally expect $KK^{bar}N$ bound state below $\Lambda^*+K$ and $f_0(a_0)+N$

**questions**

- does KN repulsion spoil bound state ?
- are the attractions too strong to hadronic molecular picture ?