J-PARC での原子核・ハドロン物理

京大基研　大西　明

- Nuclear and Hadron Physics Experiments at J-PARC
- Hypernuclear Physics
  - Ξ hypernuclei, Double Λ hypernuclei
- Mesons in Nuclei
  - Pionic atoms and nuclei, Kaonic nuclei, Medium modification of meson spectral func.
- Exotic Hadrons
- Summary

Experiments at J-PARC

Japan Proton Accelerator Research Complex (J-PARC)

http://j-parc.jp/

J-PARC Experiments at 50 GeV

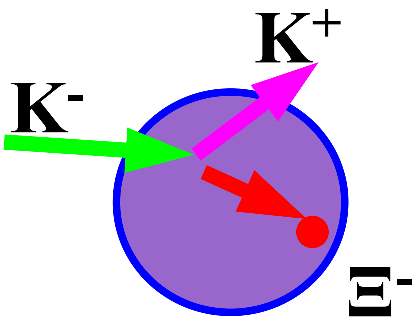
- **J-PARC Proposals in Nuclear and Hadron Experiments**
  http://j-parc.jp/NuclPart/Proposal_e.html
  - **Hypernuclear Physics: 10 (P03, P05, P07, P10, P13, P18, P22, LoI x 3)**
    - **S=-1, -2 nuclei / atoms, YN interaction, Weak decay**
  - **Mesic Nuclei / Atom: 6 (P15, P16, P17, LoI x 3)**
    - **Kaonic nuclei / atoms, Mesic nuclei, Medium modification of meson masses**
  - **Exotic Hadron: 3 (P09-LoI, P19, LoI x 1)**
    - **Penta quark, Penta quark nuclei**
  - **Structure Functions: 4 (P04, P12-LoI, P23, P24)**
  - **Neutrino Physics: 2 (P11, LoI)**
  - **Weak Processes 3 (P06, P14, P21-LoI)**

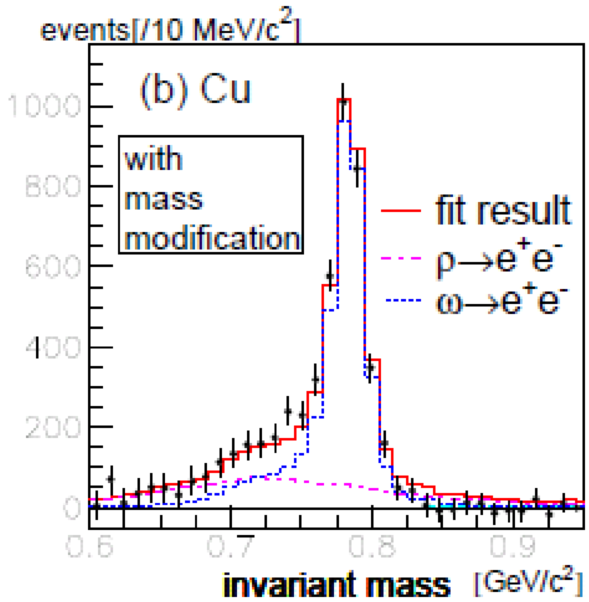
I'm sorry but I can cover only this part

Wide scope in Paritlce, Hadron and Nuclear Physics

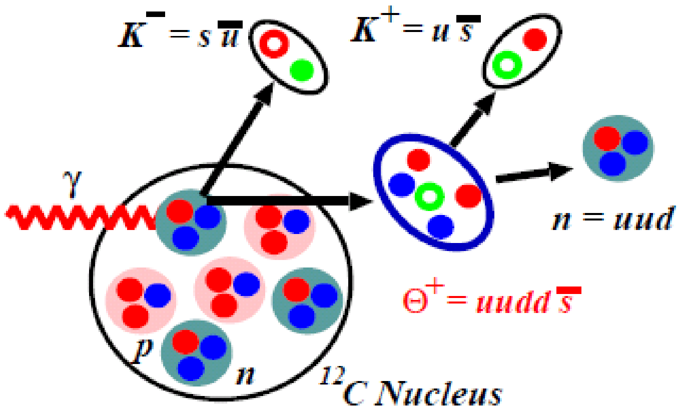
Wha do we expect to observe at J-PARC ?

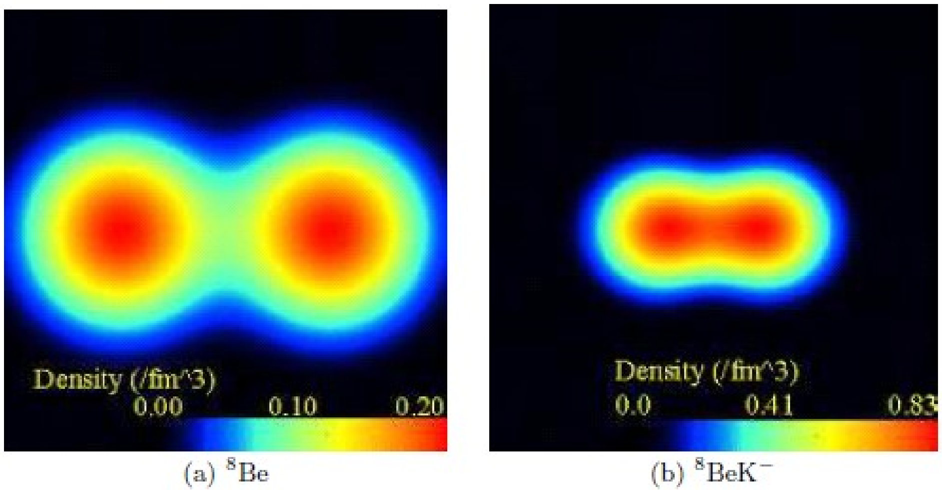
- S=-2 核、YN 散乱、弱崩壊
- 中間子 (Kbar, ω, η) 核 / 原子、質量変化
- ペンタクウォーク





Naruki et al. (KEK-PS-E325), 2006



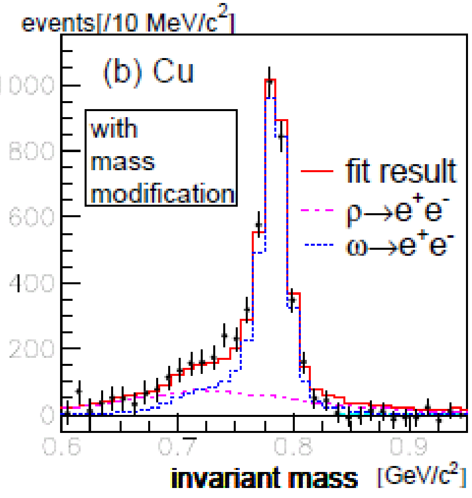


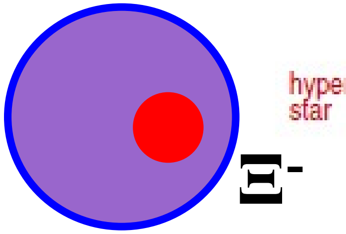
(a) ^{8}Be (b) ^{8}BeK$^-$

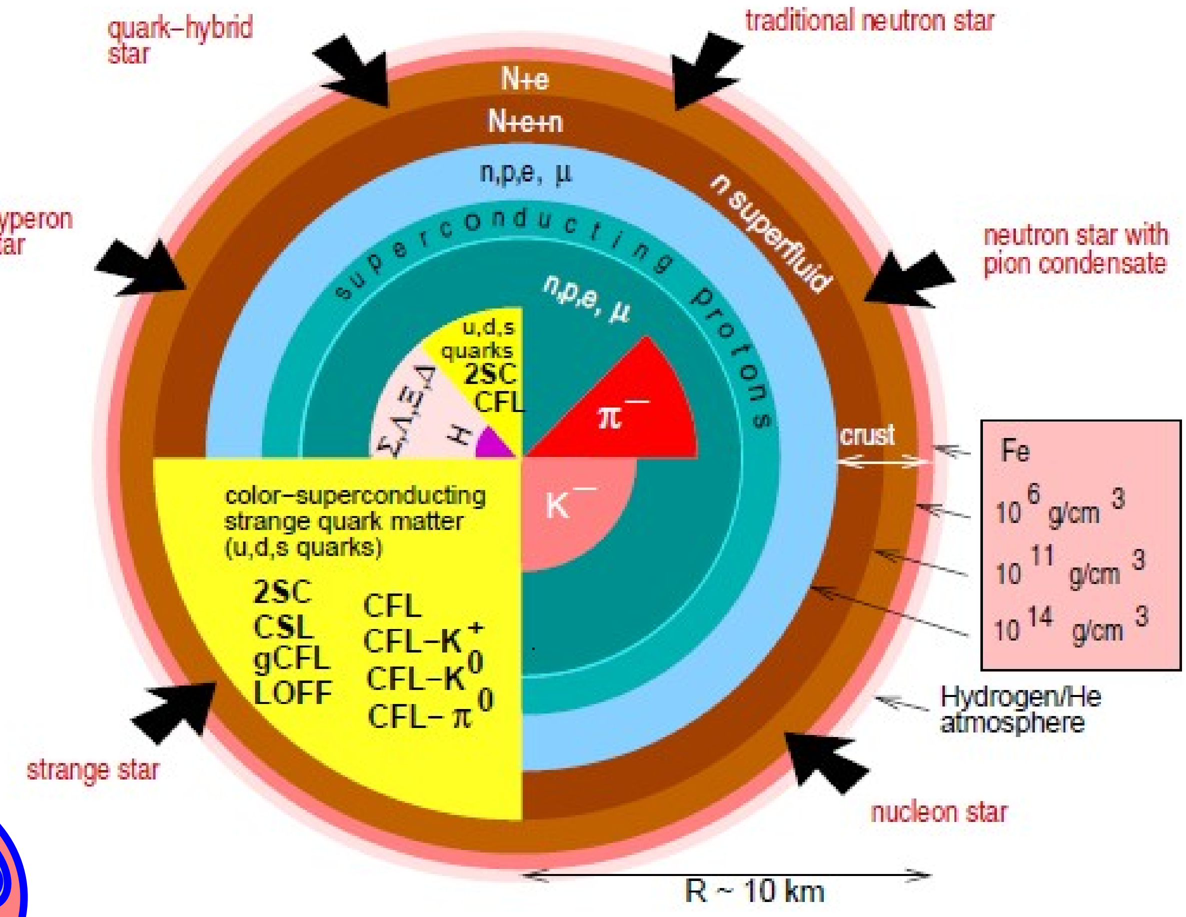
Dote, Akaishi, Horiuchi, Yamazaki, 2004

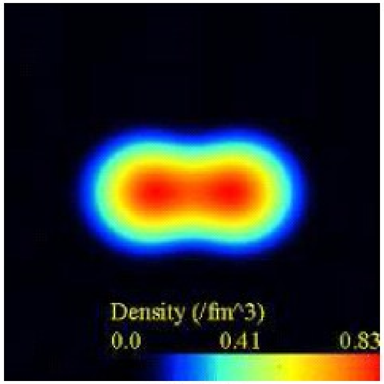
Which phase is realized in neutron stars ?

- **J-PARC の物理**
  → 中性子星物質の性質解明への決定的役割を期待！
  実験室のクォーク多体系から Dense QCD へ

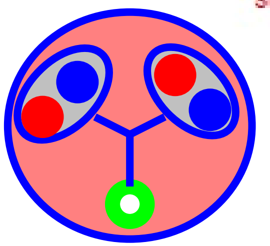






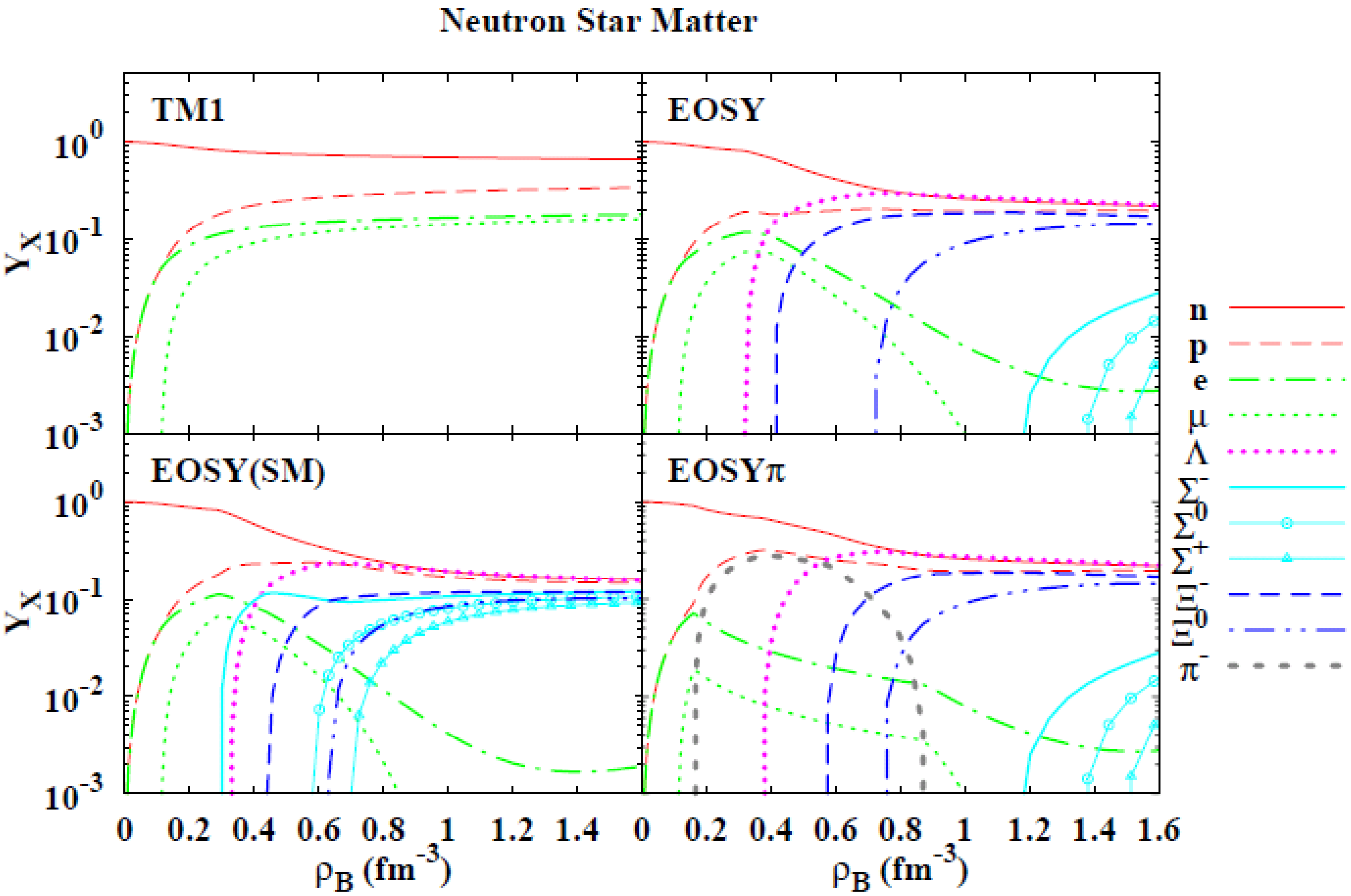


(b) ^{8}BeK$^-$



F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193

Particle Composition in Neutron Star

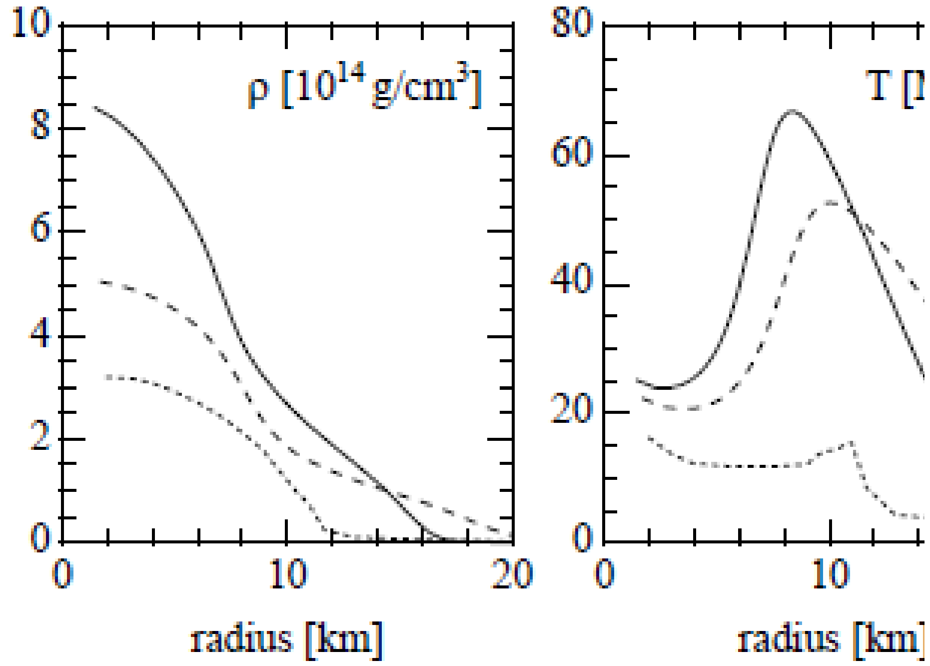


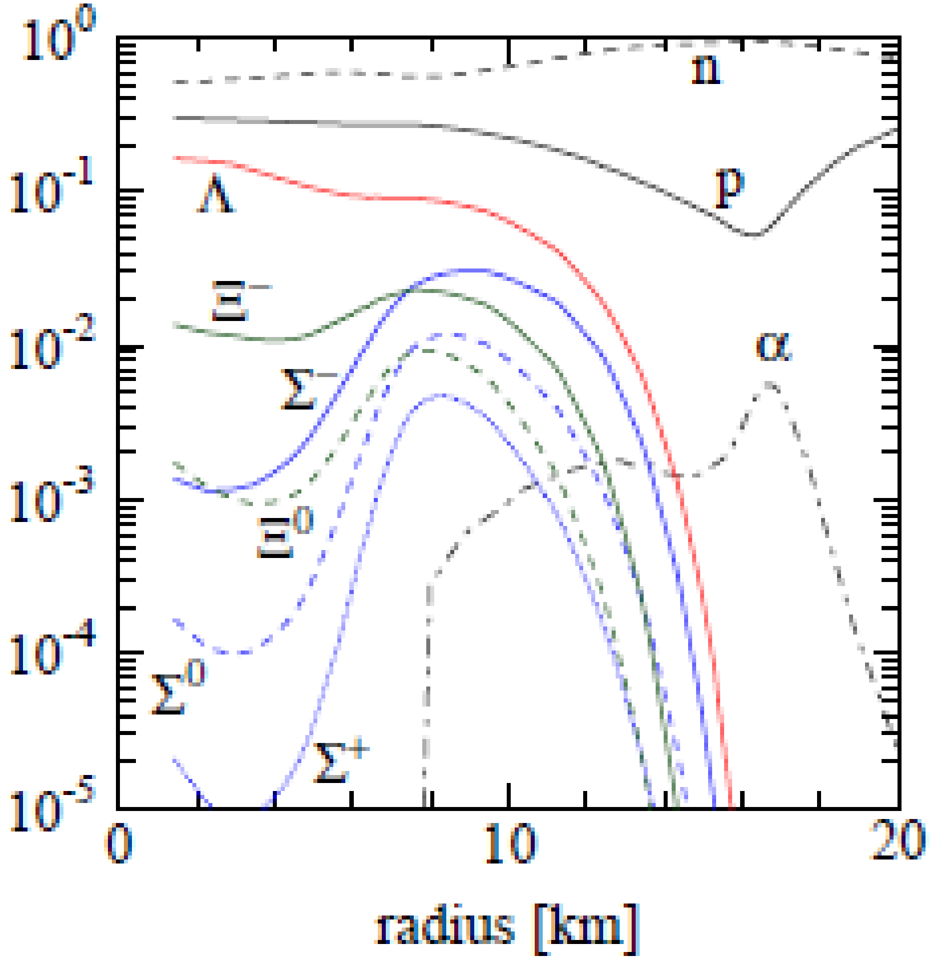
U_Ξ = -15 MeV, U_Σ = + 30 MeV

Ishizuka et al., JPG35(2008)

Hyperons during Black Hole Formation

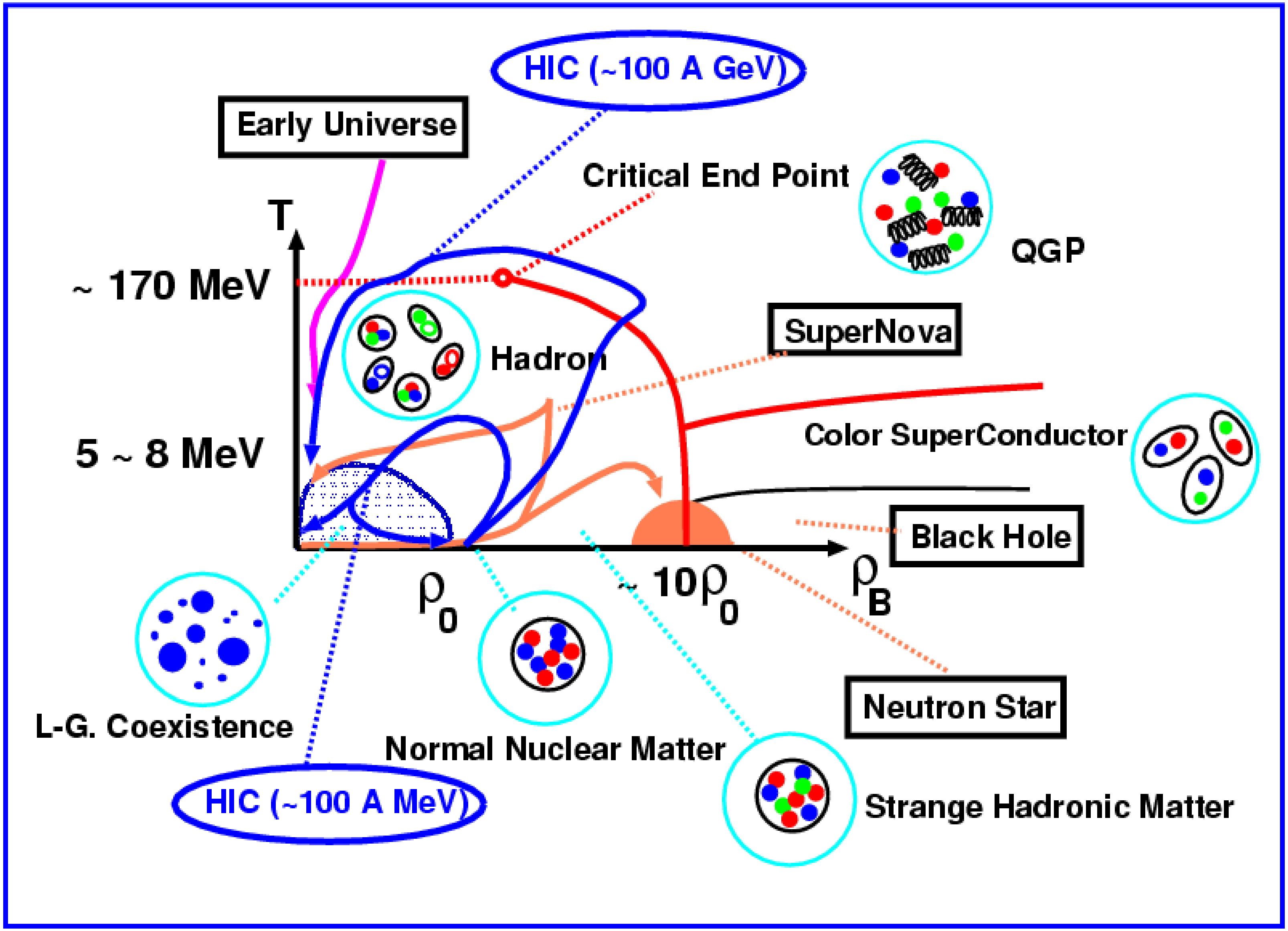
- ブラックホール形成過程にもハイペロンは大きく寄与





Sumiyoshi et al. in prep.

Quark / Hadron / Nuclear Matter Phase Diagram



Rich Structure / Astrophysical implications / Accessible in HIC

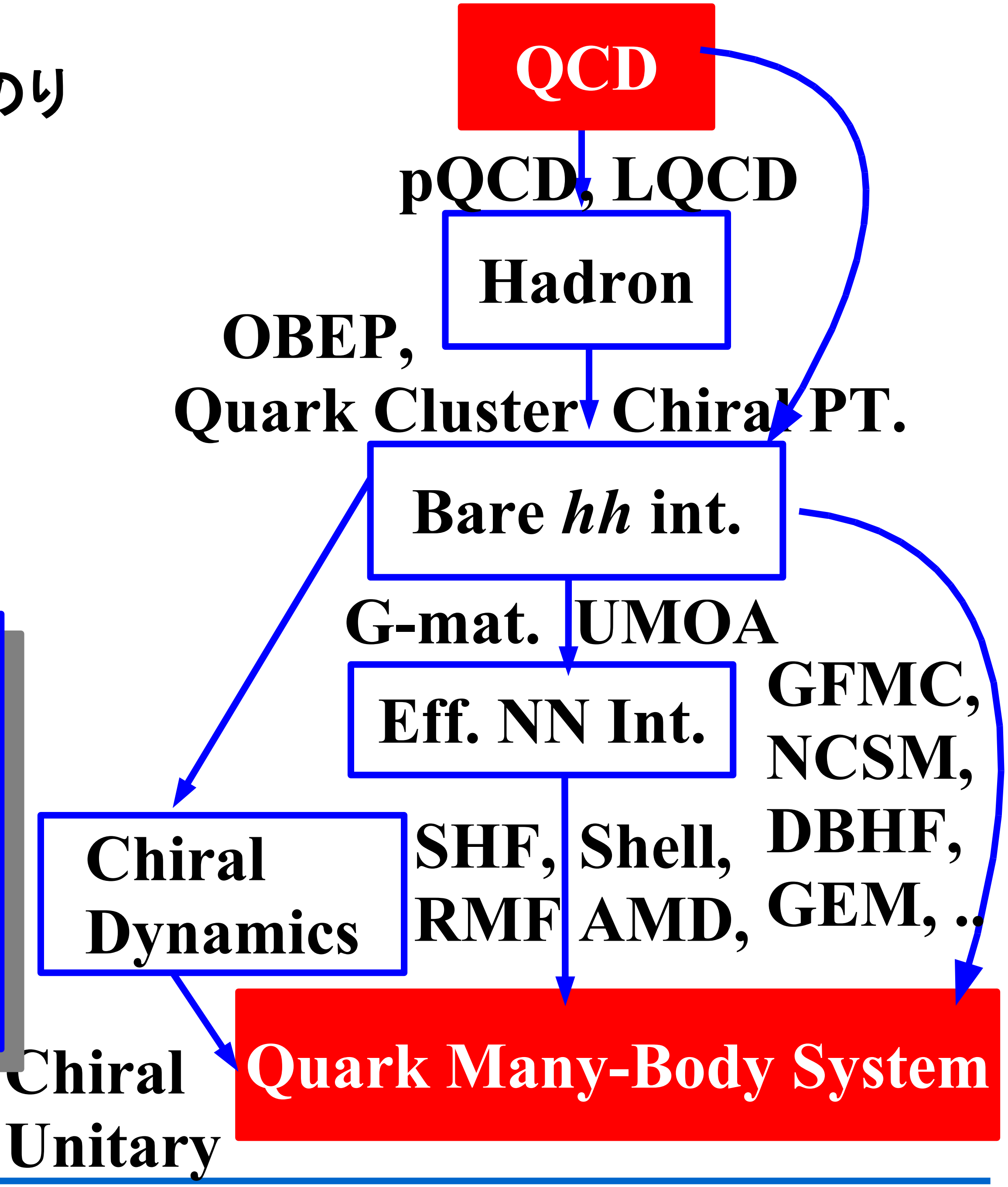
Nuclear and Hadron Physics at J-PARC: Dense QCD

- クォーク多体系の物理
  - クォーク･グルーオン → 「ハドロン、共鳴ハドロン → ハドロン多体系」
    → 束縛状態、共鳴を作るエネルギースケールでは QCD は非摂動論的
    格子 QCD で直接議論できる「クォーク多体系」は限られている
  - 多ストレンジネス原子核、エキゾチック･ハドロン、中間子原子核、...
    → 多くの「未発見」の状態が待っている
- Dense Matter (高密度物質) の物理
  - 中性子星コア、超新星爆発過程、ブラックホール生成過程
    → 原子核密度の数倍 (10^{15} g/cc) にも達する高密度状態の EOS が
    コンパクト天体現象のダイナミクスを規定
  - カラー超伝導、高バリオン密度 QGP 、Quarkyonic 物質、K 凝縮、π 凝縮、ハイペロン混合、$^3P_2$ 超伝導、パスタ原子核、.....
    → 相互作用が主要な役割を果たす多彩な相の存在可能性
    ただし、実験的根拠は弱い

Nuclear and Hadron Physics at J-PARC: Dense QCD

- QCD から高密度物質を含む「クォーク多体系」への長い道のり
  - 正しく理解を進めるには、それぞれの段階 (階層) での
    「相互作用」、
    「構造 (波動関数) 」、
    「反応機構」
    の検証が必要
  - 「新しい状態」の発見には、それ自体で大きな価値

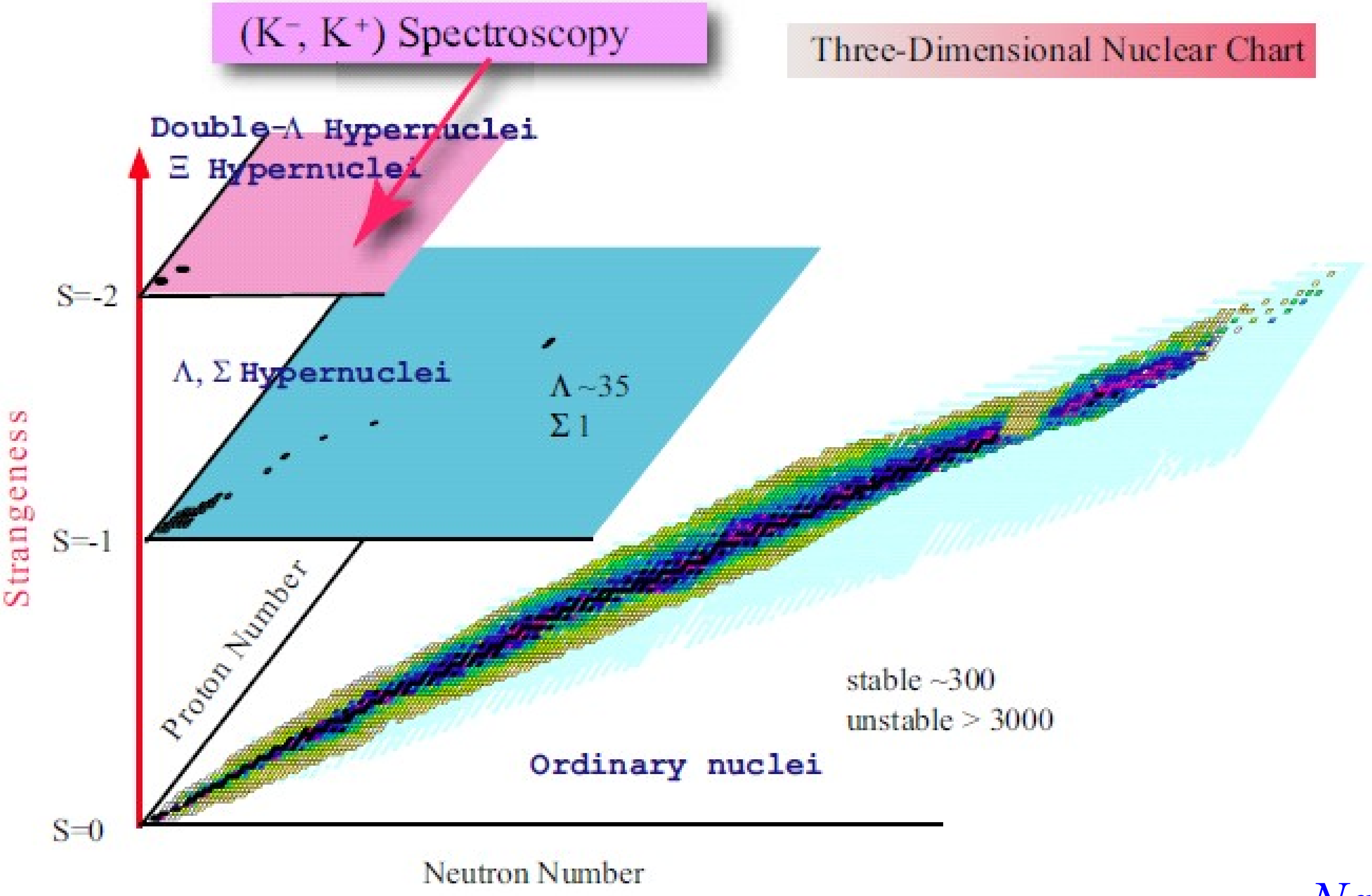
Dense QCD @ J-PARC
データに基づく高密度物質の記述を念頭において、
クォーク多体系の
深い理解と
新しい存在形態の発見
を目指す。



Hypernuclear Physics

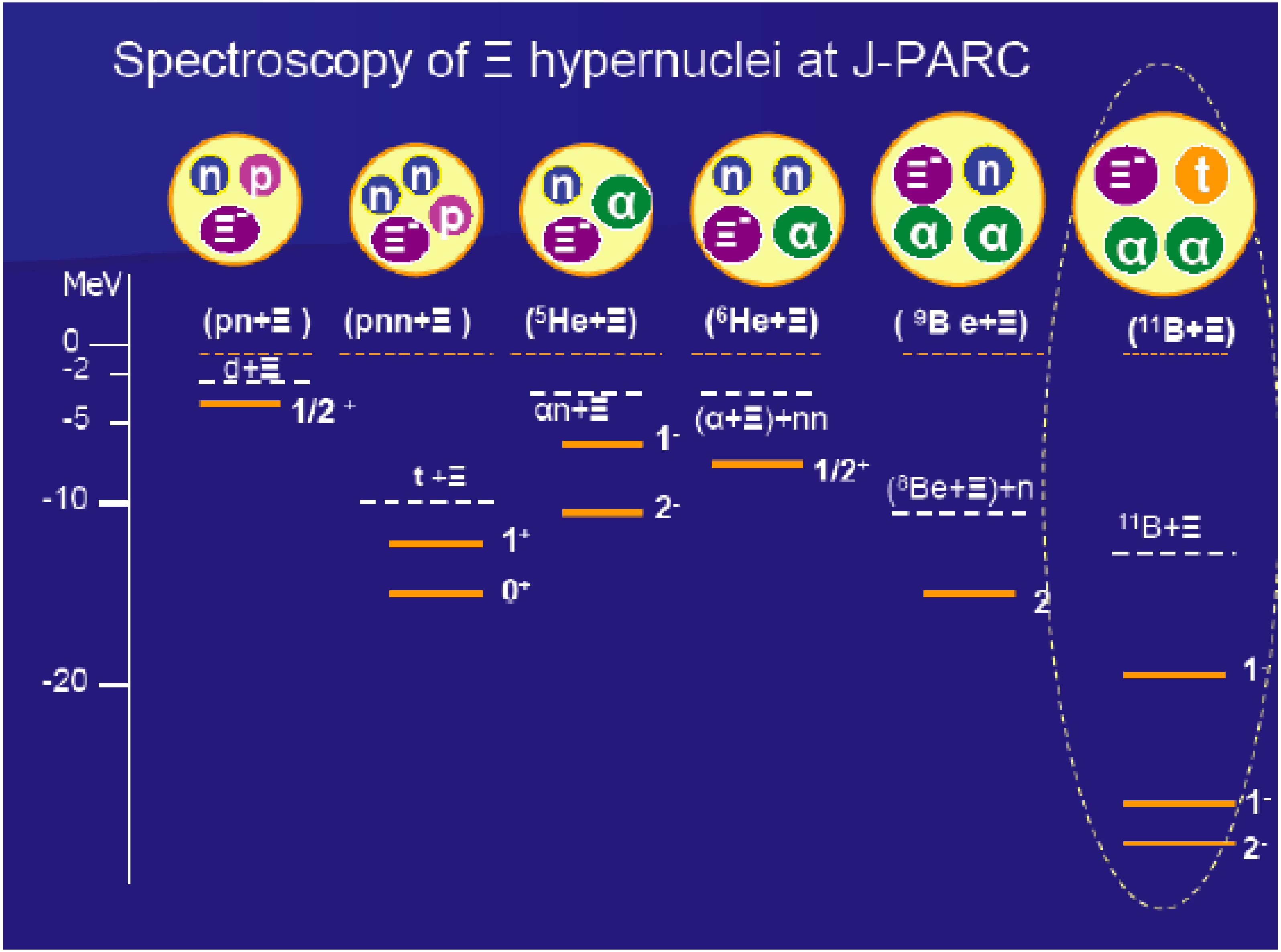
Hypernuclear Chart

- **Hypernuclear Physics at J-PARC =「発見」と「系統化」**
  → まずはΞ核の発見と分光



Nagae

Ξ hypernuclei



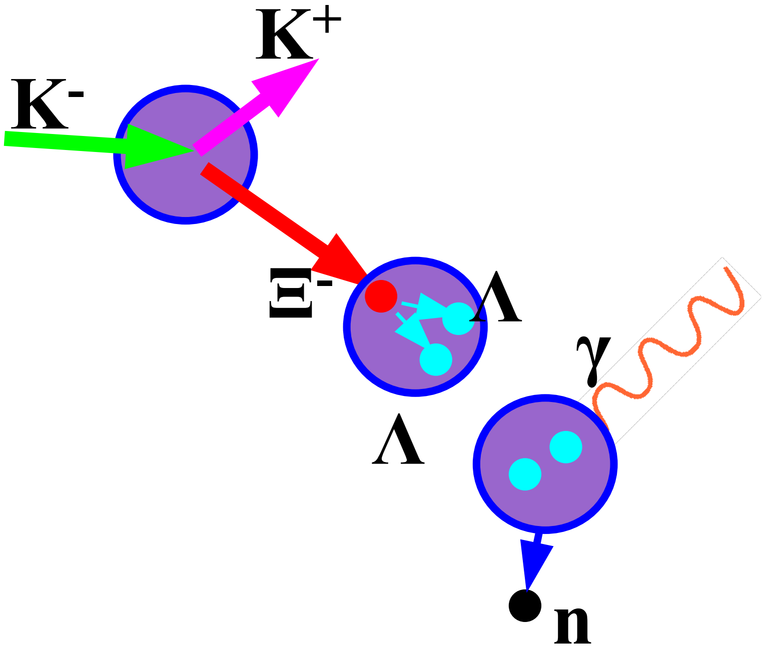
Spectroscopy of Ξ hypernuclei at J-PARC

Hiyama et al.

Why is Ξ interesting ?

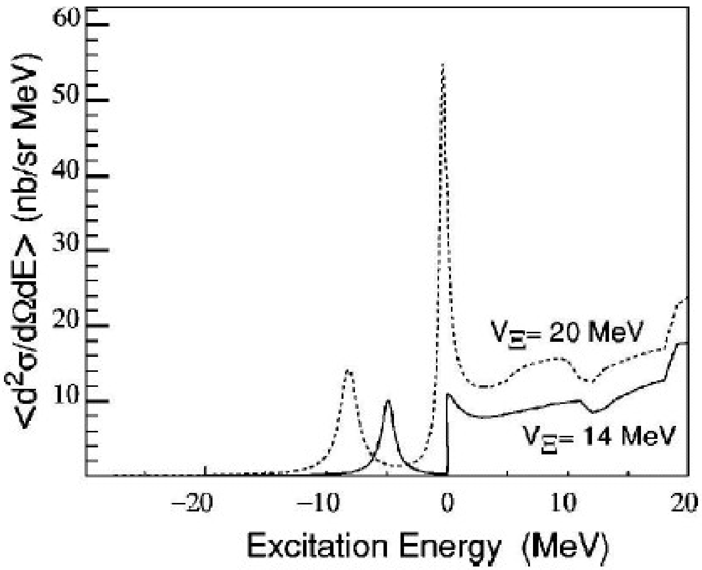
P03: X rays from Ξ- Atom (Tanida)
P05: Ξ-Hypernucleus, Ξ12Be, via the 12C(K-,K+) Reaction (Nagae)

- **Ξ 核は「多ストレンジ系」への入り口**
- **中性子星で最初に現れる負電荷バリオンはおそらくΞ^-**
- **ΞN 相互作用はバリオン間相互作用の模型に大きく依存**
- **Ξ 核の離散ピーク はまだ誰も見つけていない！**

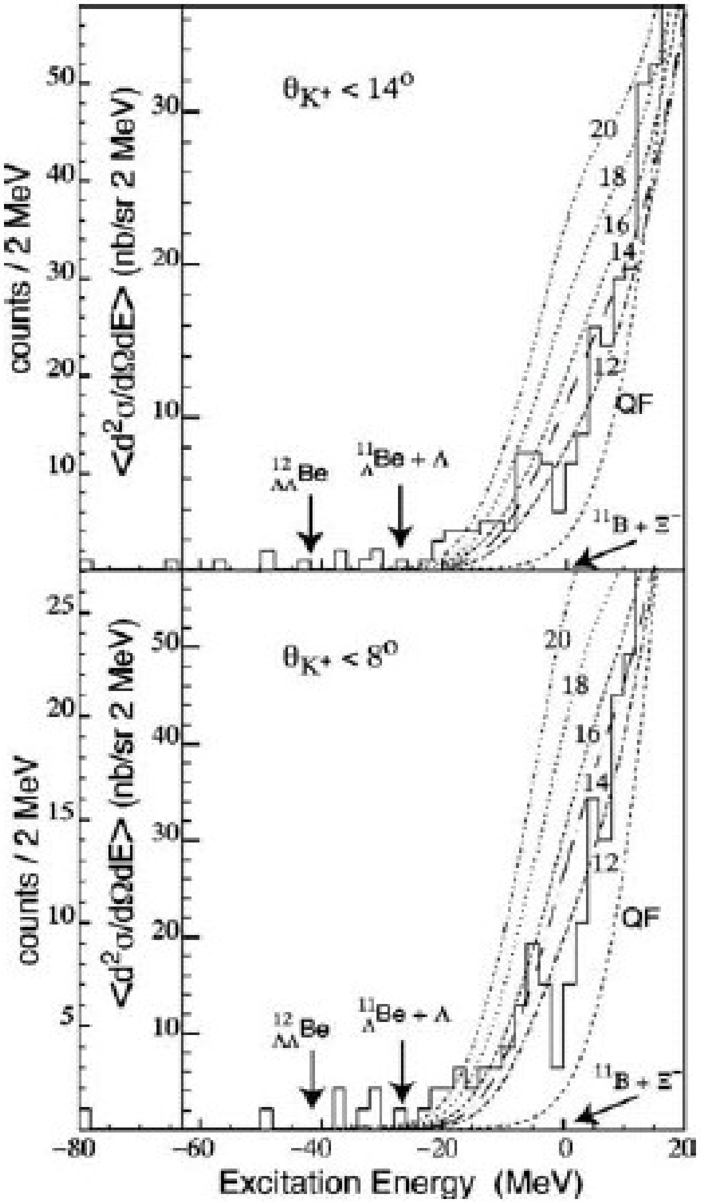


Ξ-Nucleus Potential; Current Status

- **Old Conjecture: $U_\Xi \sim -(24\text{-}30)$ MeV From Emulsion Data (Dover, Gal)**
- **Recent Data favor shallow potential $U_\Xi \sim -(12\text{-}15)$ MeV**
  - **Twin Hypernuclear Formation** *(Aoki et al.)*
  - **(K-, K+) spectrum in the bound region** *Khaustov et al.(BNL-E885)*

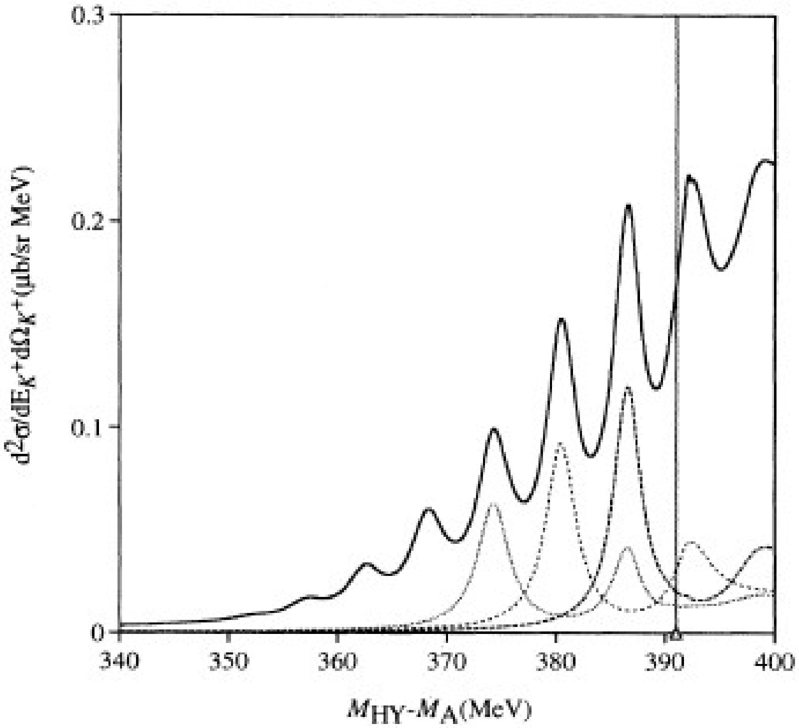


E885 (BNL)

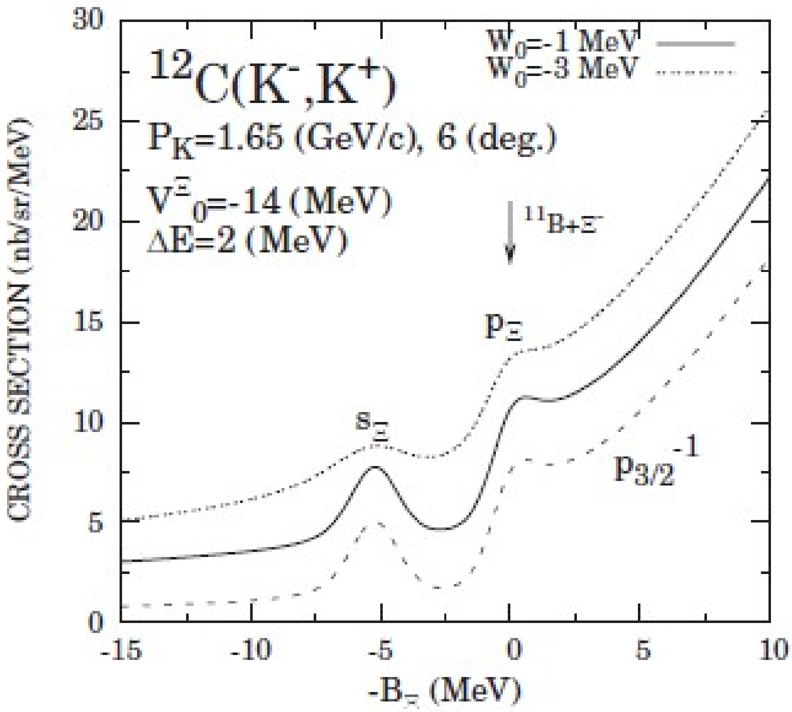


(K-,K+) Spectra: Potential Model Results

- **Day 1 Experiment: C(K-,K+) $^{12}{}_{\Xi}$Be Reaction**
  - **DWIA (Green's Function Method) Evaluation with V=-14 MeV potential**
    → As far as resolution is good (ΔE<= 3 MeV)
    and conversion width is small (W=-1 MeV),
    Bound state peaks will be observed.



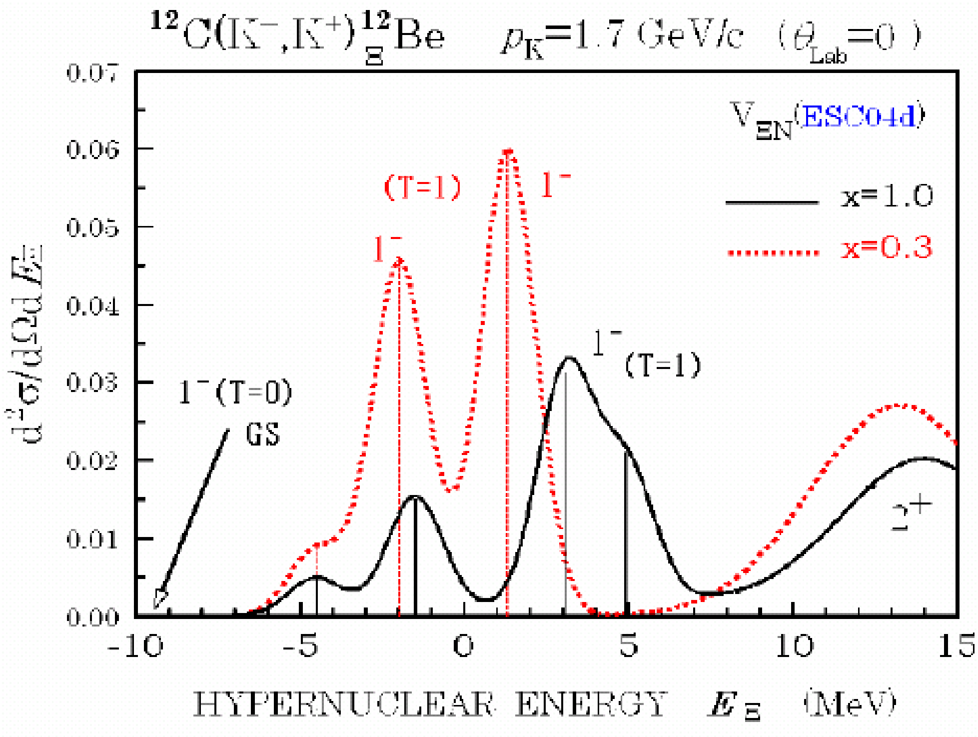
Tadokoro, Kobayashi, Akaishi, 1995



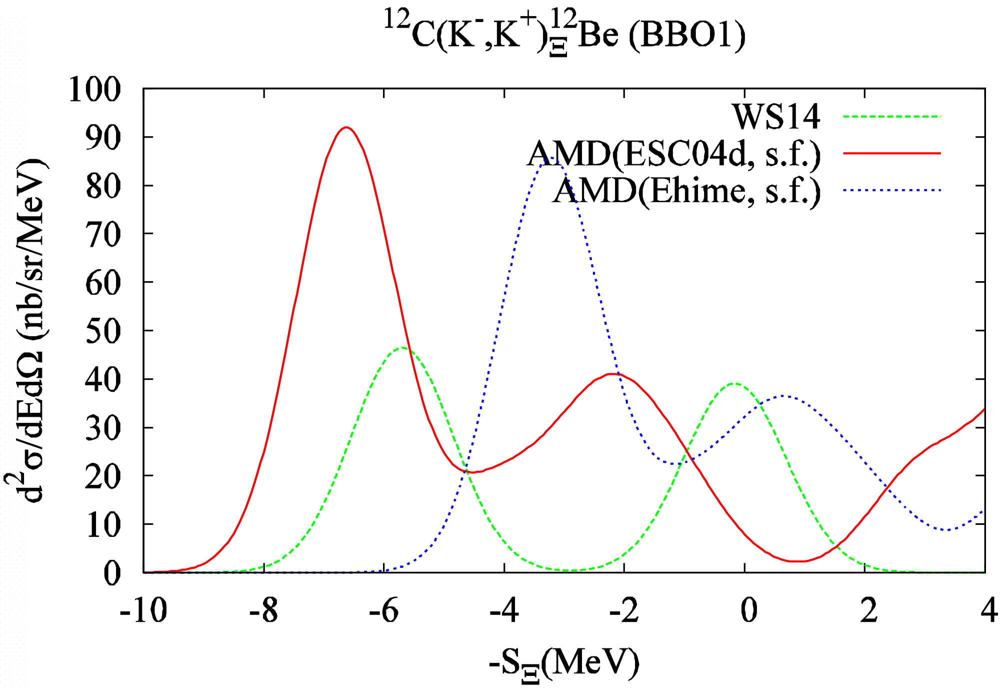
Maekawa, Tsubakihara, Matsumiya, AO, arXiv: 0704.3929

(K-,K+) Spectra: Shell model and AMD

- **ΞN interaction giving V ~ - 14 MeV**
  - **NHC-D, Ehime, ESC04d**
- **Shell model results + DWIA (cf. Motoba's talk)**
  - **Spin dependence of ΞN interaction → Fragmentation of strength**



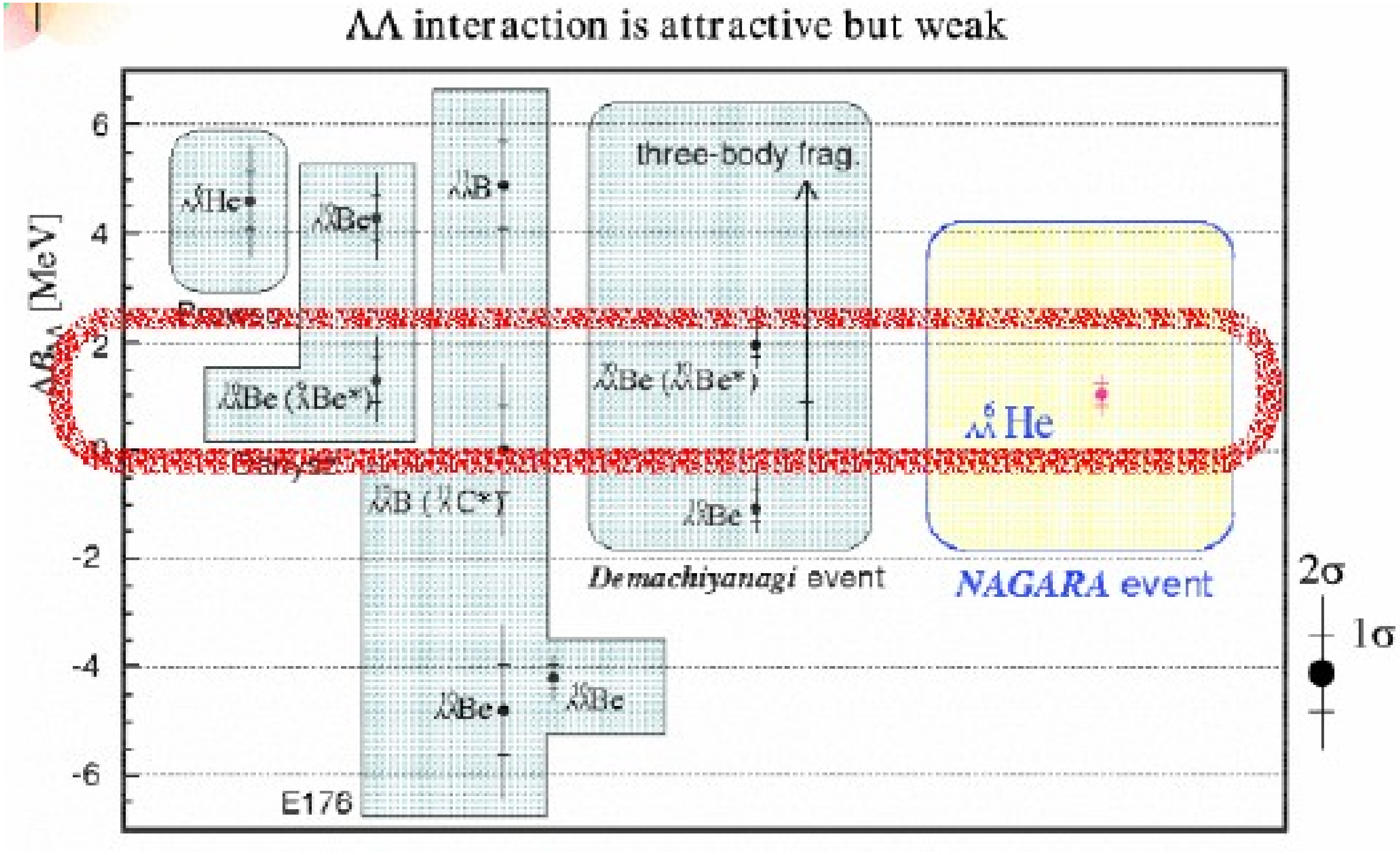
Sugimoto, Motoba, Yamamoto, Hiyama, 2007



Matsumiya, Tsubakihara, Kimura, Dote, AO (Matsumiya's talk)

Double Λ Nuclei

- **Nagara event**
  これまでに発見された中で、ユニークに解釈できる唯一のダブル Λ 核

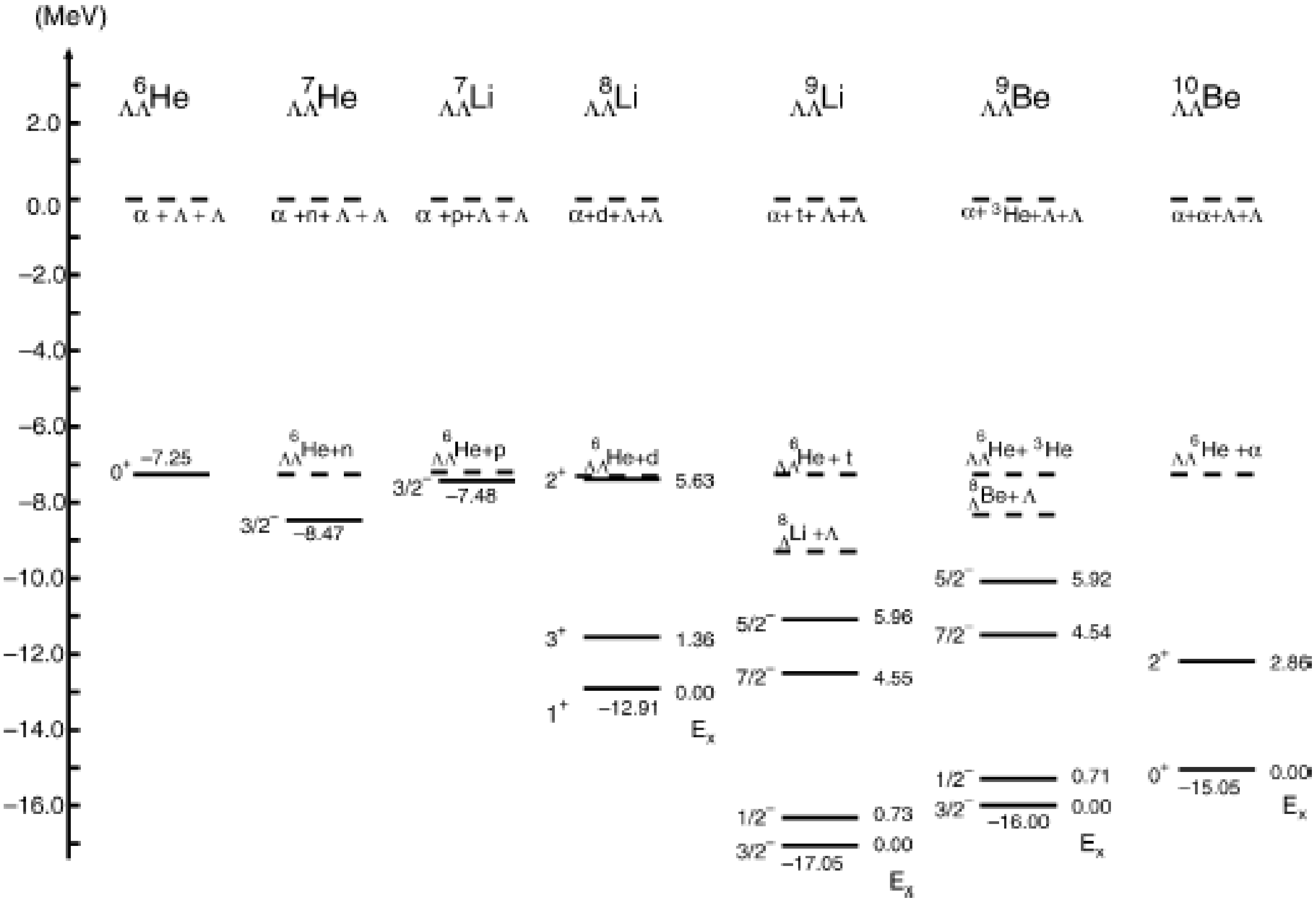


Nakazawa

Double Λ Nuclei

P07: S=−2 Systems with an Emulsion−Counter Hybrid Method (Imai, Nakazawa,Tamura)

- **発見から系統性へ！**
  → 100 個のダブル Λ 核 @ J-PARC

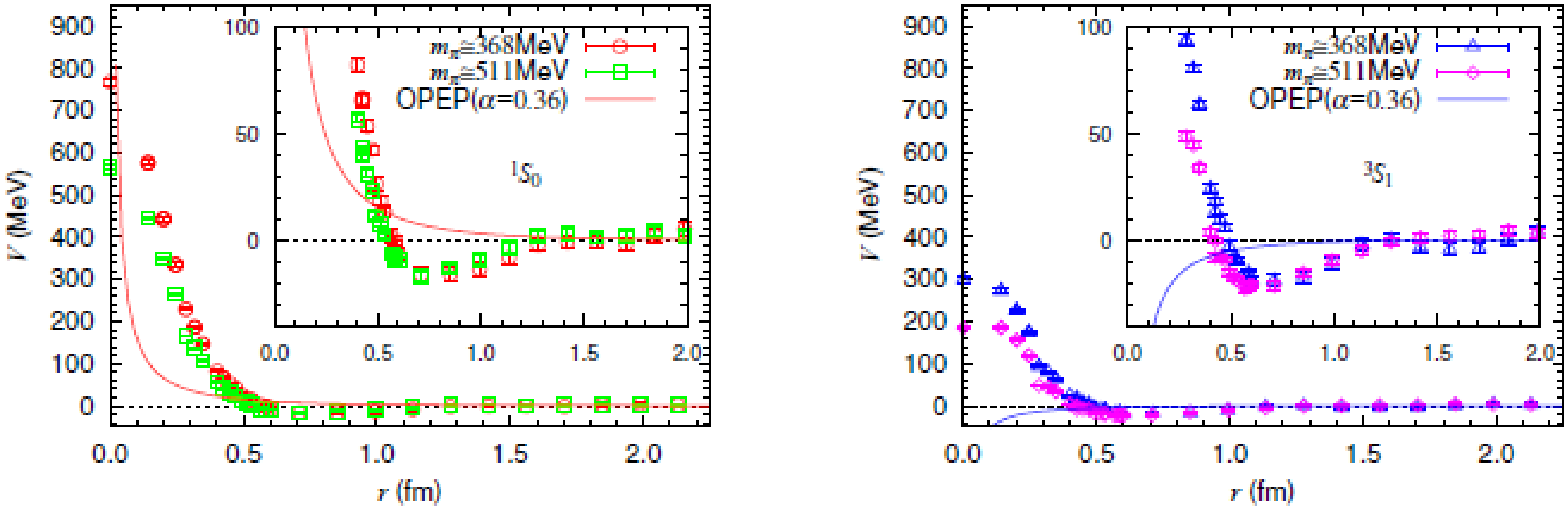


Hiyama et al., 2002

Hyperon-Nucleon Scattering

LoI: YN Scattering Experiment using a SCIFI-MPPC System (Miwa)

- **YN 散乱実験**
  - **バリオン間相互作用を定める最も直接的なデータ**
  - **「第一原理」計算との直接比較が可能となりつつある（格子 QCD)**



Nemura, Ishii, Aoki, Hatsuda, arXiv:0806.1094

Other Hyernuclear Experiments

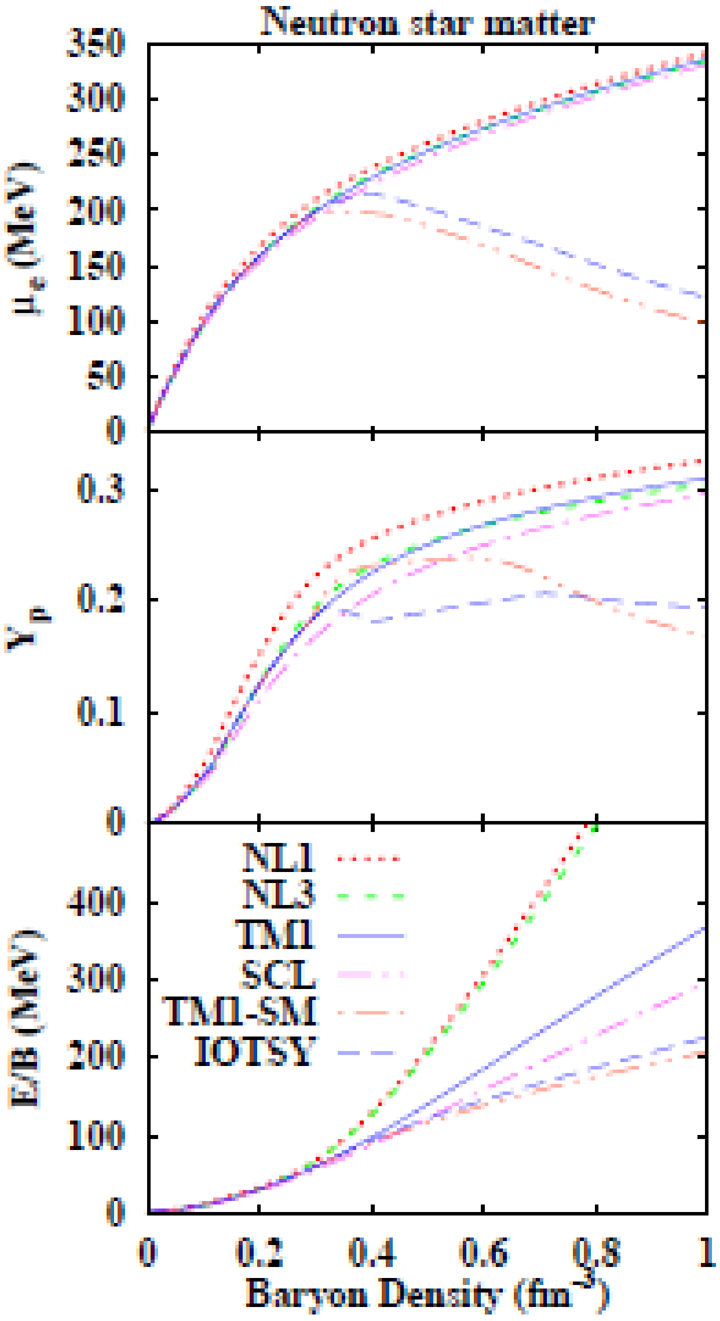
- **Spectroscopy of Λ hypernuclei**
  → ΛΣ mixing, Precise ΛN Int., ...
  - **P10: n-Rich Λ-Hypernuclei with the DCX (Sakaguchi)**
  - **P13: Gamma-ray spectroscopy of light hypernuclei (Tamura)**
  - **LoI: Gamma-ray spectroscopy of hypernuclei at K1.1 (Tamura)**
- **Weak decay of Λ hypernuclei**
  → Non-mesic decay, Multi-nucleon absorption, Asymmetry, ...
  - **P18: Weak Decay of $^{12}_{\Lambda}$C and the three-body weak int. process (Bhang, Outa, Park)**
  - **P22: Exclusive Study on the ΛN Weak Int. in A=4 Λ-Hypernuclei (Sakaguchi)**
- **Σ hypernuclei**
  → Second Σ Nucleus, YN interaction
  - **LoI: Study of Σ-N interaction using light Σ-nuclear system (Tamura)**

Mesons in Nuclei at J-PARC

Mesons in Neutron Stars

- **中性子星の中で、中間子は「構成粒子」となりうるか？**
  - **p-wave π 凝縮**
    Sawyer; Migdal;
    Kunihiro,Takatsuka,Tamagaki, Tatsumi
  - **K 凝縮**
    Kaplan-Nelson;
    Muto, Tatsumi, Fujii, Maruyama
  - **s-wave π condensation ?**
    $\mu_e > m_\pi$ in neutron star matter in RMF
    しかし π- 核ポテンシャルは斥力だから、
    s-wave 凝縮は起こらない (?)

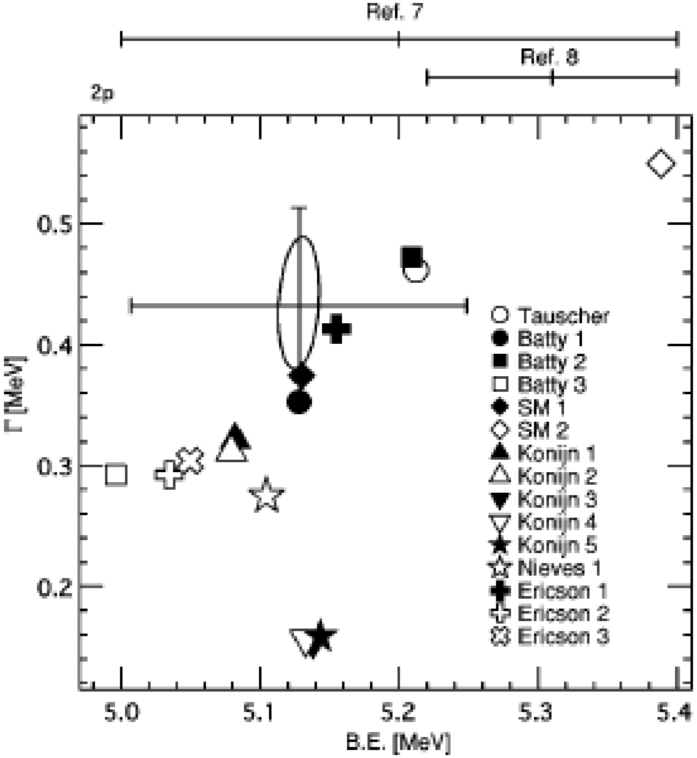
中間子の感じるポテンシャルの深さ (or self-energy) が凝縮の存否を決定する → J-PARC での物理へ

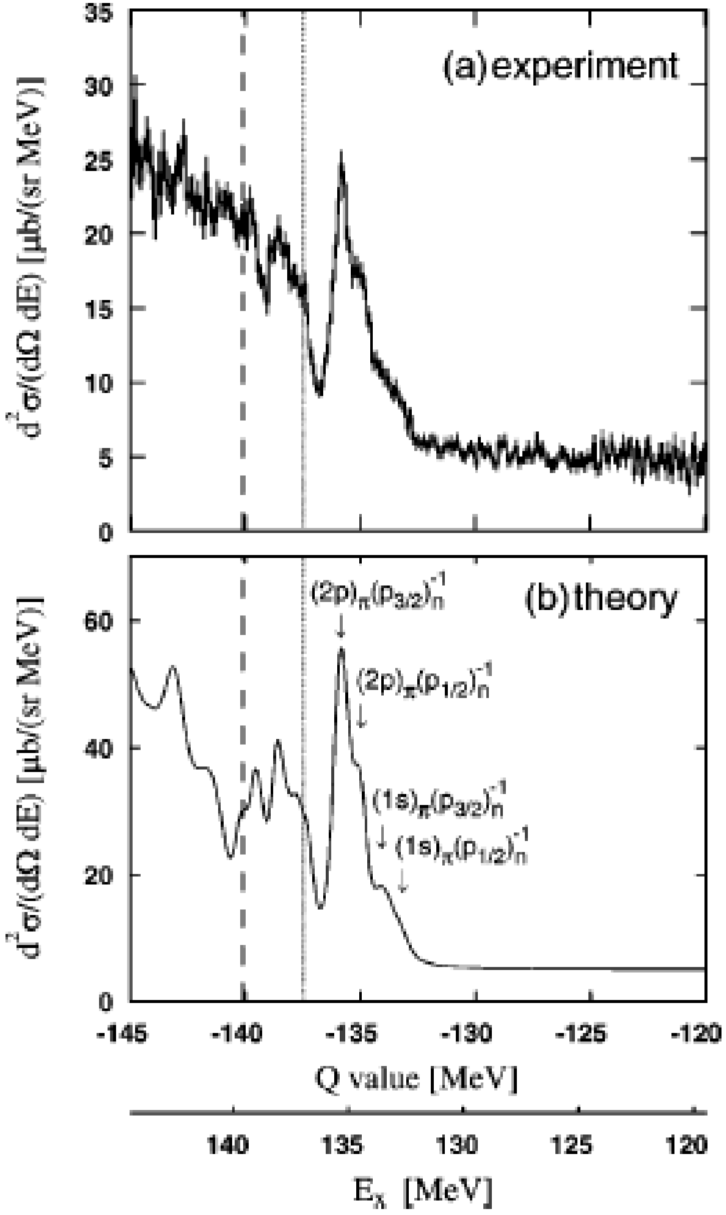


Pionic Atom and Pion Potential in Nuclear Matter

- **π-Nucleus Potential**
  - **Pionic Atom (Pb, Sn) and Scattering**
    → s-wave π- 核ポテンシャルの深さは
    $\rho \sim 0.6\ \rho_0$ においてよく決まってきた

$$U(\pi^-) = -\frac{2\pi}{m_\pi}\left[\left(1+\frac{m_\pi}{M_N}\right)(b_0\rho_B + b_1\delta\rho) + \left(1+\frac{m_\pi}{2M_N}\right)\mathrm{Re}B_0\,\rho_B^2 f(Y_p)\right]$$

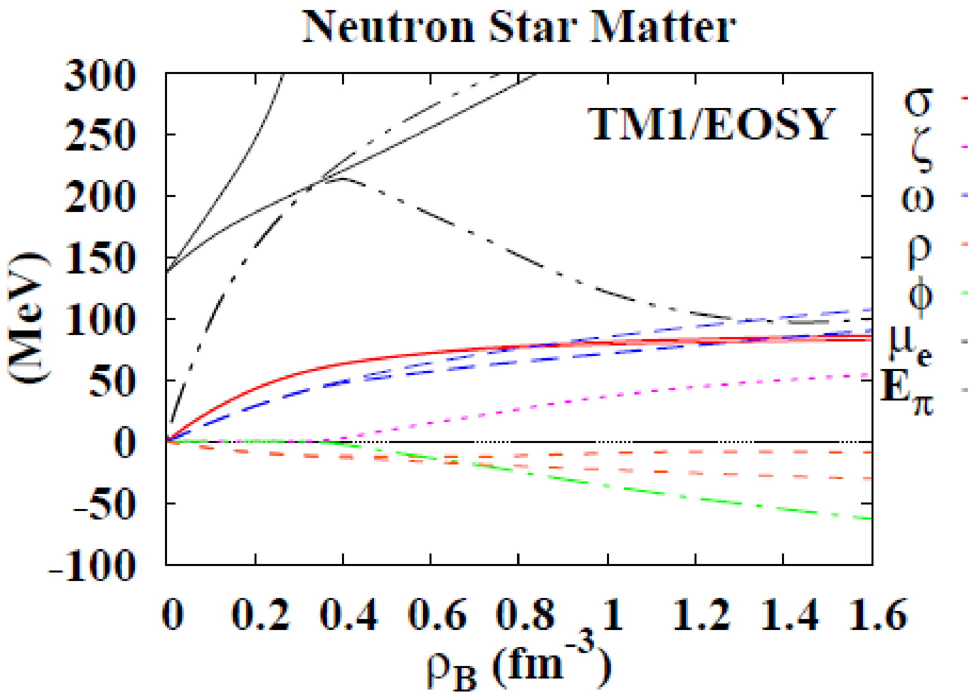


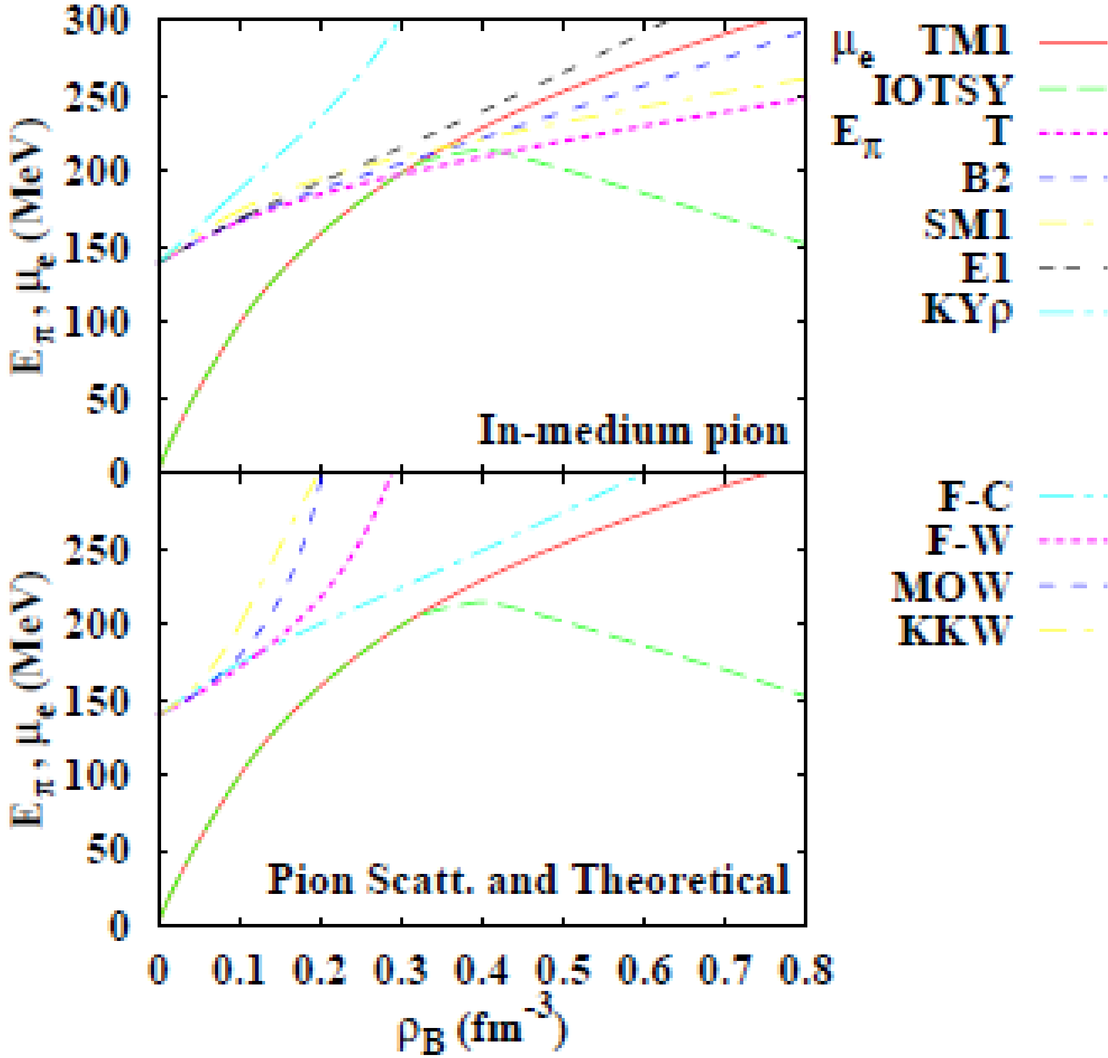


Itahashi et al., 2000

s-wave π condensation in neutron stars ?

- **中性子星物質中での π のエネルギー**
  - **Batty et al., 1983**
    Pb データをほぼ説明
  - **Kienle-Yamazaki, 2004**
    Sn isotope データまで説明



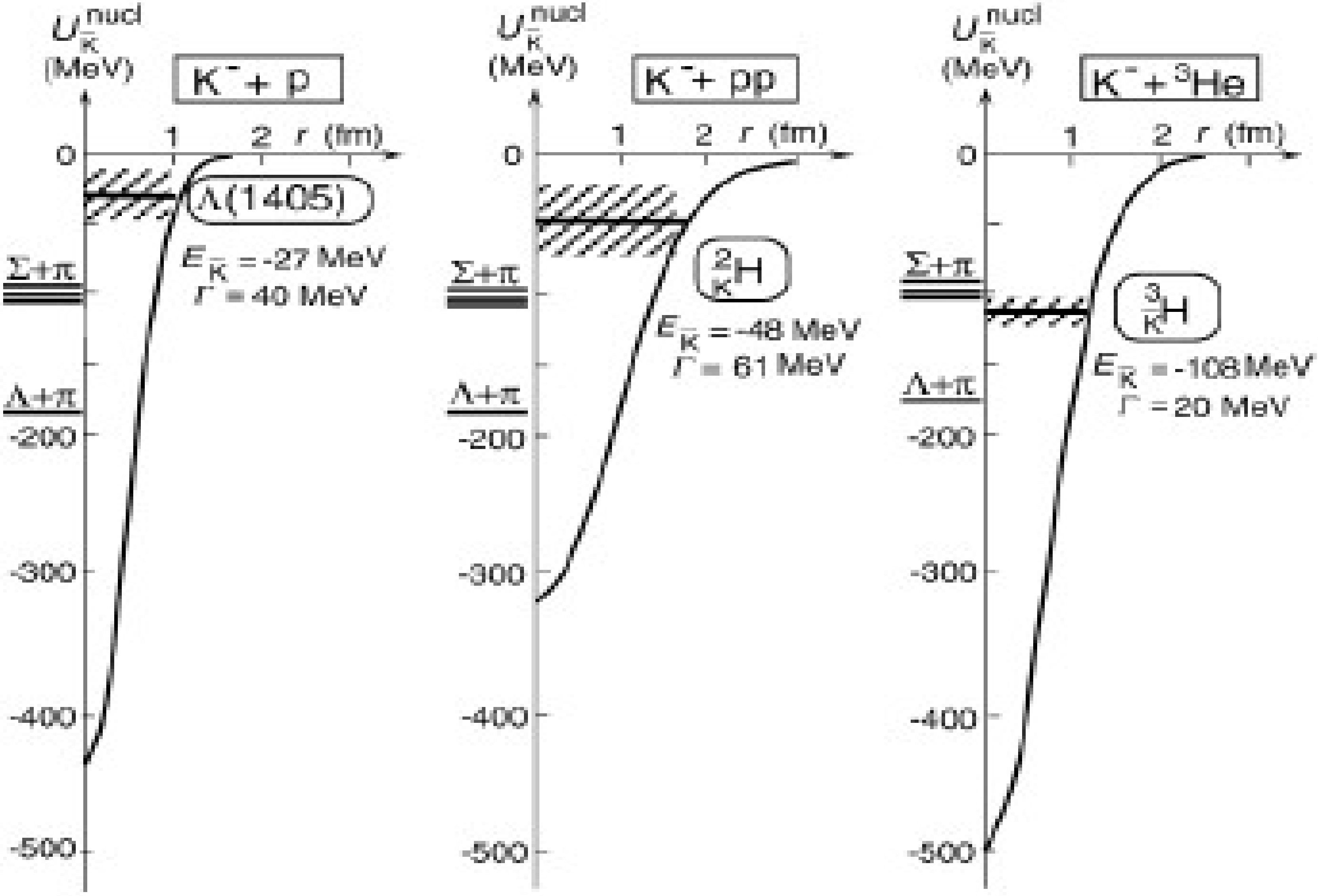


b_1 パラメータの密度依存性
→ No s-wave pion cond.

深く束縛されたK 中間子核

- 出発点
  - Kbar-N 相互作用はもともと引力のはずだが、
    低エネルギー散乱、K 中間子水素では斥力に見える
    (Martin, 1981; Iwasaki et al. 1997)
  - Kbar-N の「束縛状態」Λ(1405) と直交するために波動関数に節が必要
    (Dalitz et al., 1967; Siegel, Weise, 1988)
  - Kbar が深く束縛すれば、もともとの強い引力が顔をだすはず
    (Koch, 1994; Waas et al., 1994; Masutani, 1988)
- どの程度束縛するか？
  - AY potential + G-matrix (Akaishi, Yamazaki, 2002; Dote et al., 2004)
    → V ~ - 200 MeV, B.E. ~ 100 MeV, Γ ~ (20-40) MeV
  - Chiral Unitary Model + Pauli blocking + π, Kbar self-energy (E-dep.)
    (Ramos, Oset, 2000; Siegel, Kaiser, Weise; Jido et al.)
    → V ~ -(40-60) MeV, B.E. ~ (10-55) MeV, Γ ~ (90-110) MeV

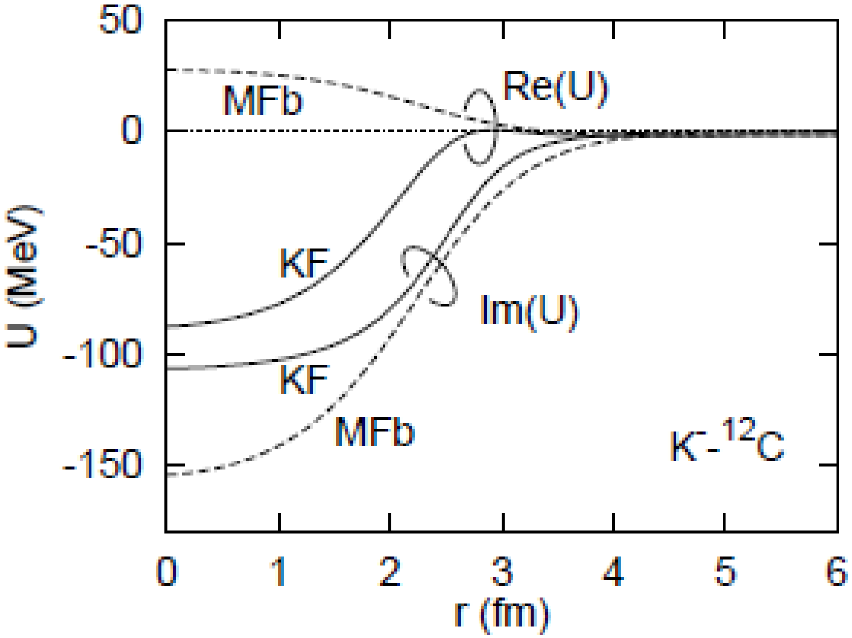
深く束縛された K 中間子核



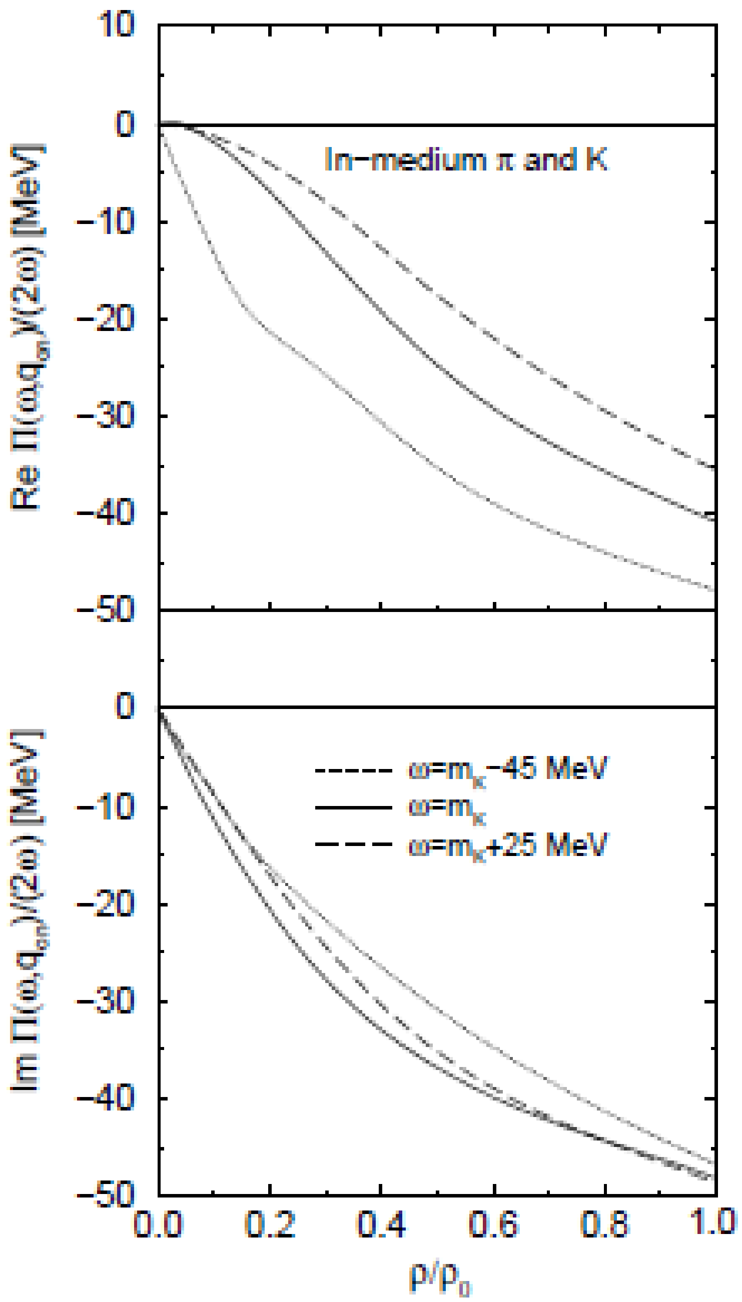
Yamazaki, Akaishi, 2002

深く束縛された *K* 中間子核

- **Several Effects may cancel !**
  - **Pauli blockin g only (AO et al.)**
    → Attractive (Koch; Waas et al., AO et al.)
  - **Self-consistency in Kbar energy**
    → Reduced attraction (Lutz)
  - **π self-energy, doule pole structure**
    → Further reduction



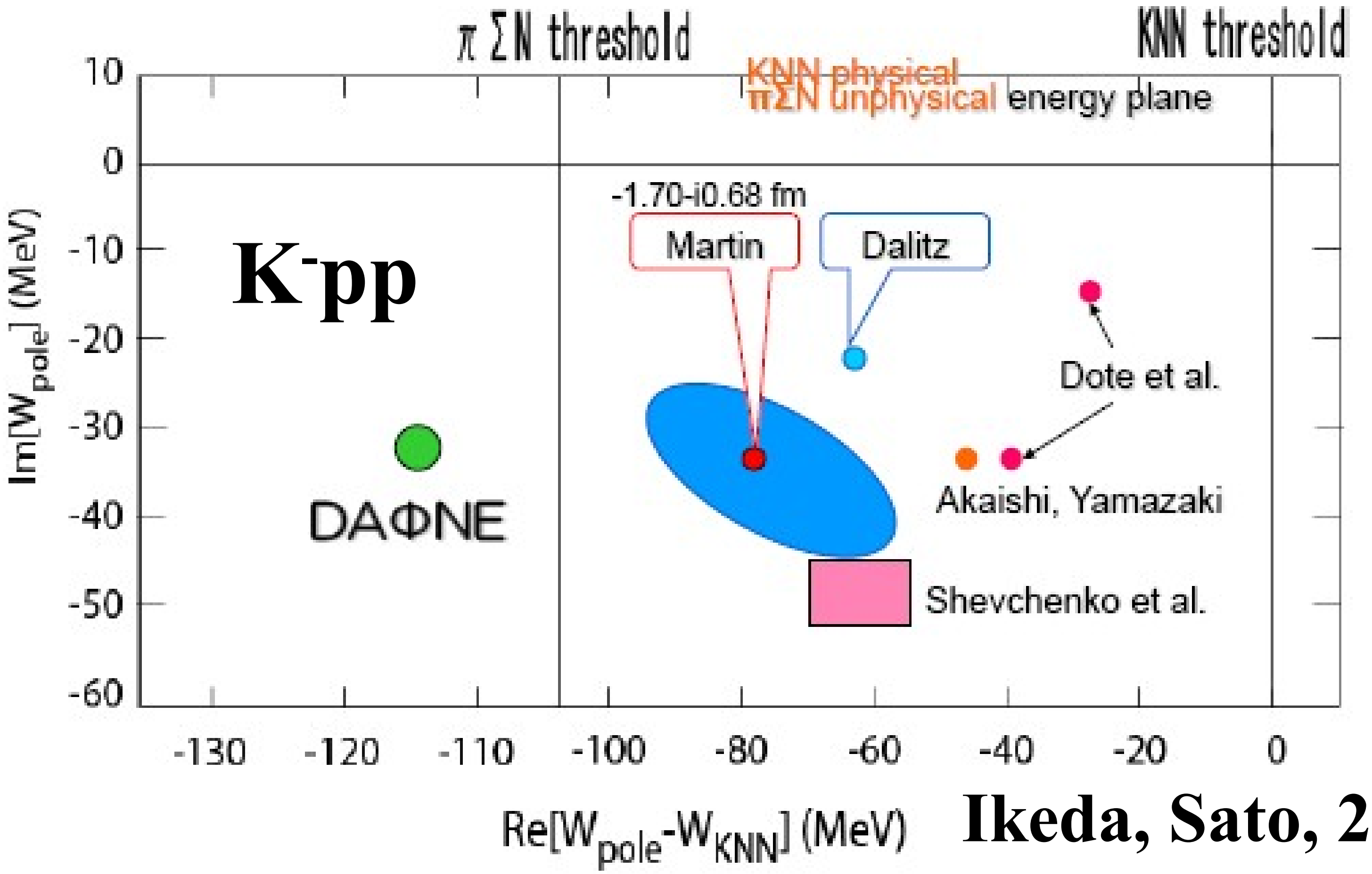
AO, Nara, Koch, 1997



Ramos, Oset, 200

深く束縛された K 中間子核

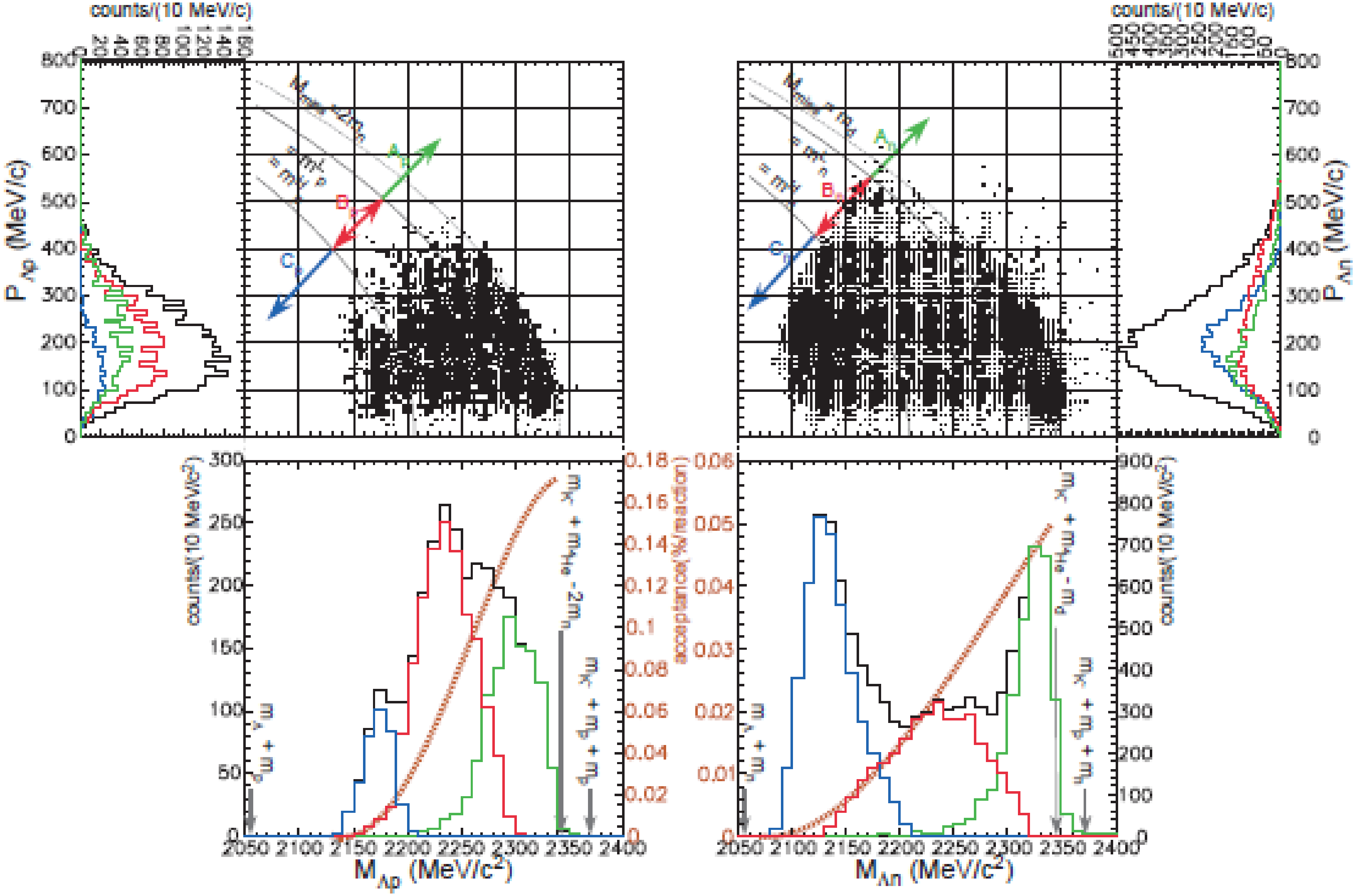
- **Short range / Tensor Correlation between baryons**
  + Channel Coupling with πY
  + Meson self-energy incl. E-dep.
  → Presice Few-Body calculation ! (Ikeda, Sato, 2007)
  (No Σ-N interaction, Separable potential)



Ikeda, Sato, 2007

深く束縛された K 中間子核

- **Experimentally, more exclusive measurement (e.g. $K^- pp \to YN$) is necessary as in E549 !**



T. Suzuki et al.(E549), arXiv:0711.4943

Hadron Mass Modification

P16: Electron pair spectrometer to explore the chiral sym. in QCD (Yokkaichi)
LoI: Nuclear ω bound state and ω mass mod. in p(π,n)ω reaction (Ozawa)
LoI: A new approach to study the in-medium ϕ(1020)-meson mass (Iwasaki)
LoI: Spectroscopy of η Mesic Nuclei by (π−, n) Reaction at Recoilless Kinematics (Itahashi)

- **Medium meson mass modification may be the signal of partial restoration of chiral sym.**

  Brown, Rho, PRL66('91)2720;
  Kunihiro,Hatsuda, PRep 247('94),221; Hatsuda, Lee, PRC46('92)R34.

- **Brown-Rho Scaling**

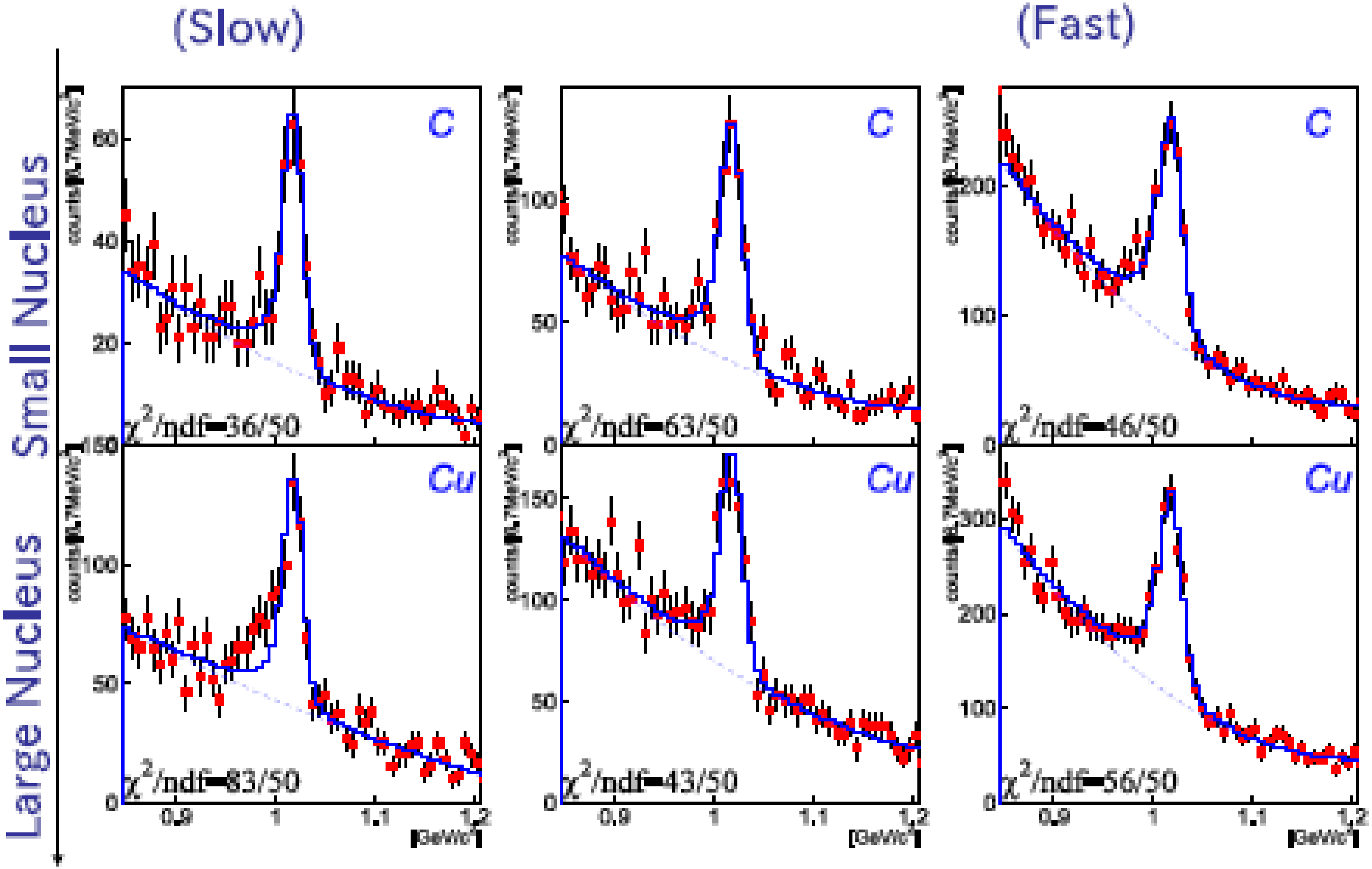
$$M^{*}_{N}/M_{N}=M^{¿}_{\sigma}/M_{\sigma}=M^{¿}_{\rho}/M_{\rho}=M^{¿}_{\omega}/M_{\omega}=f^{*}_{\pi}/f_{\pi}$$

- **Medium modification of spectral func.**
  is observed experimentally.

Interpretation is model dependent
(Mass / Width / Coupling to Res. / ...)
→ Systematic Data are Necessary !

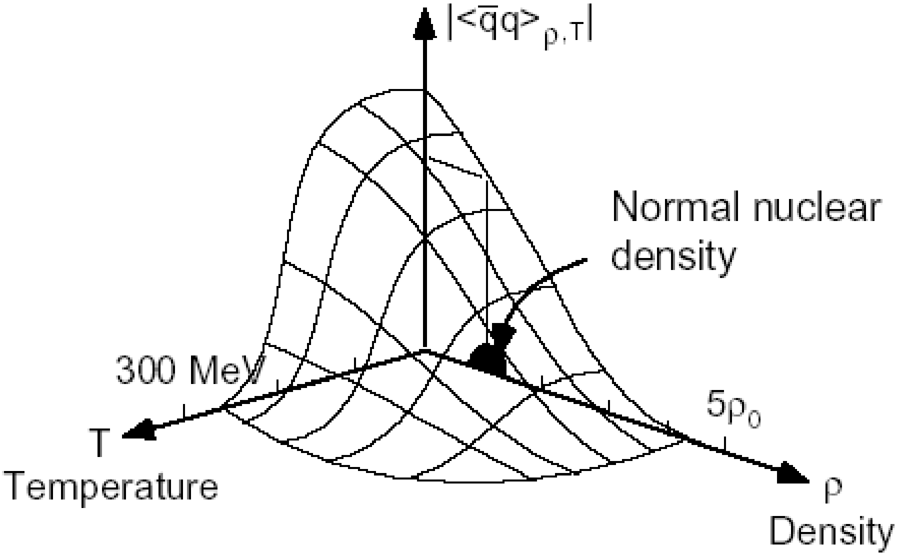
Medium Modification of Meson Masses

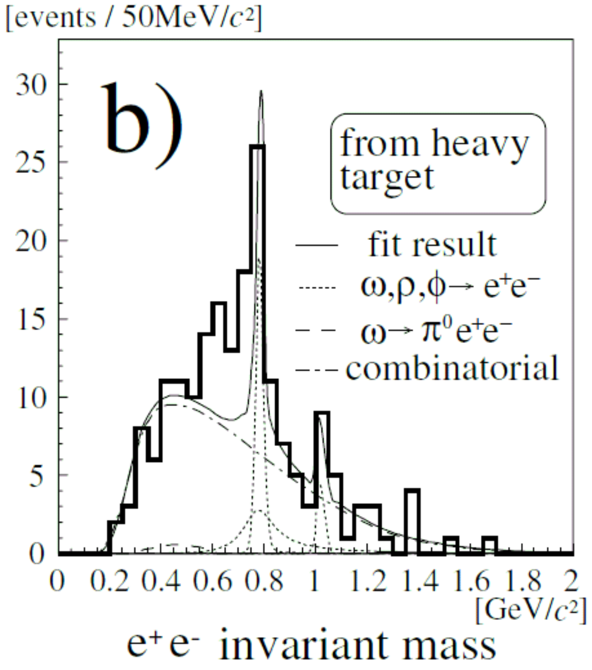
- **φ meson spectral function is modified at low p**



KEK-PS-E325

Hadron Mass Modification





KEK-E325 Collab.(Ozawa et al.), PRL86('01),5019;

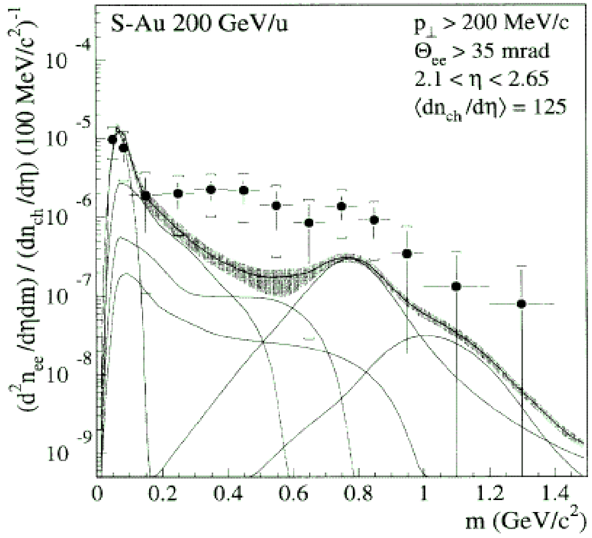
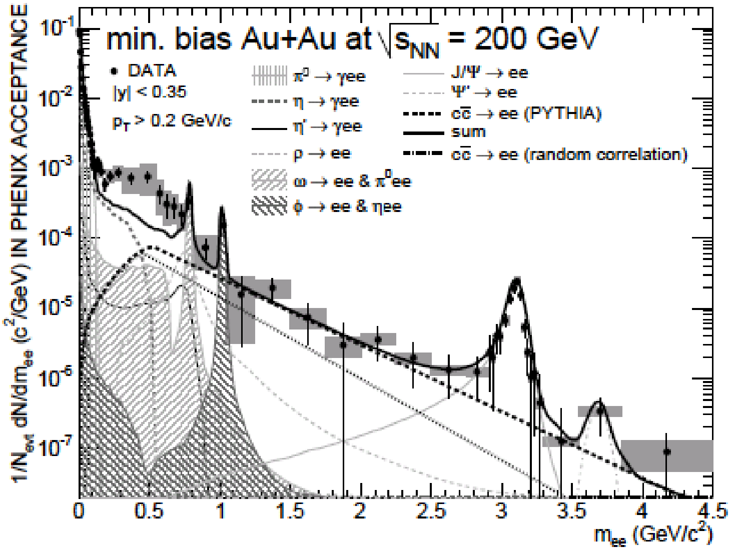


FIG. 4. Inclusive e^+e^- mass spectra in 200 GeV/nucleon S-Au collisions. For explanations see Fig. 2.

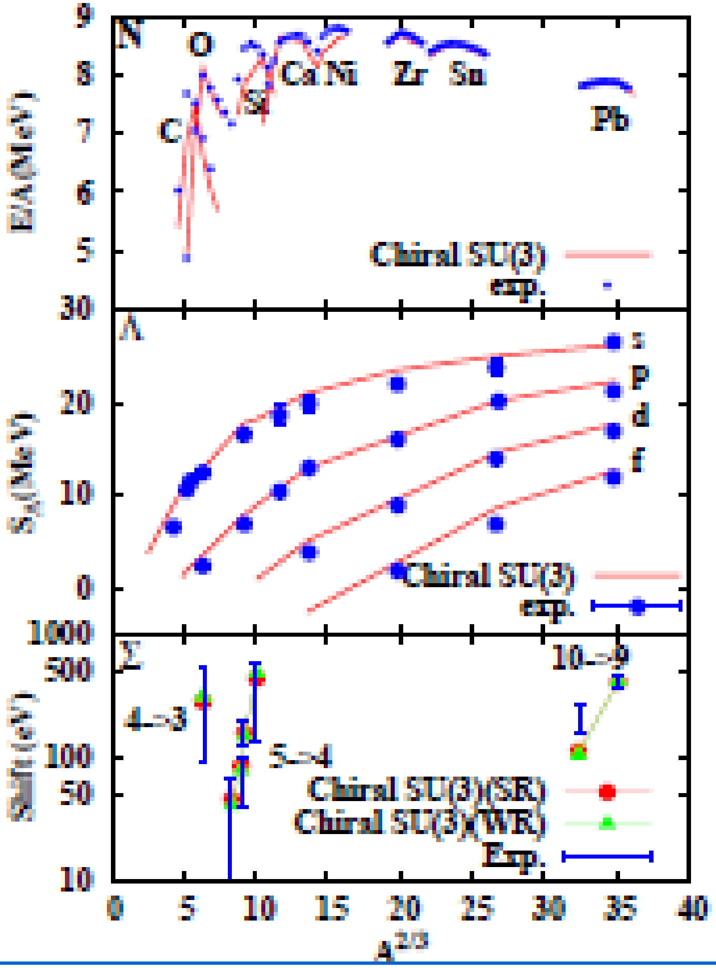
CERES Collab., PRL75('95),1272;

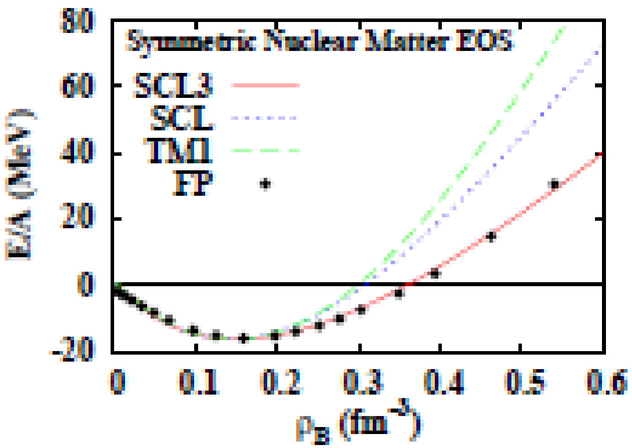


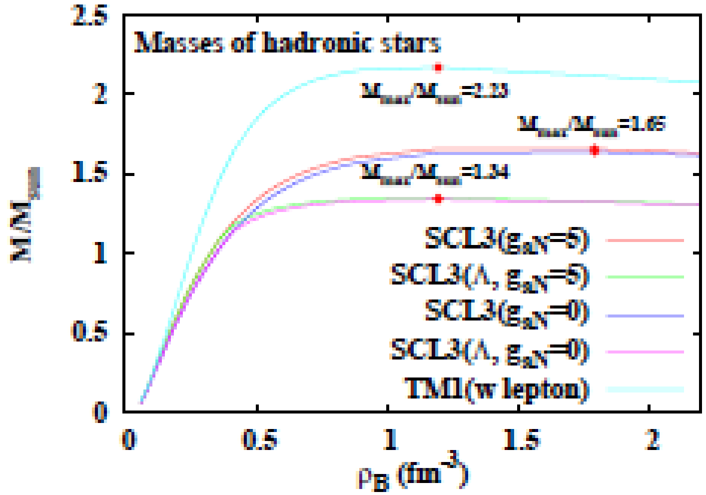
PHENIX Collab., arXiv:0706.3034

“Universal” Three-baryon Repulsion ?

- **Chiral SU(3) RMF with Hyperons**
  - **EOS ~ Variational Calc., but underestimates NS mass**
    → Universal 3B repulsion from ω mass reduction ?
    (Takatsuka, Tamagaki, Nishizaki)







Tsubakihara et al., 2008; in prep.

Exotic Hadron

Exotic Hadrons

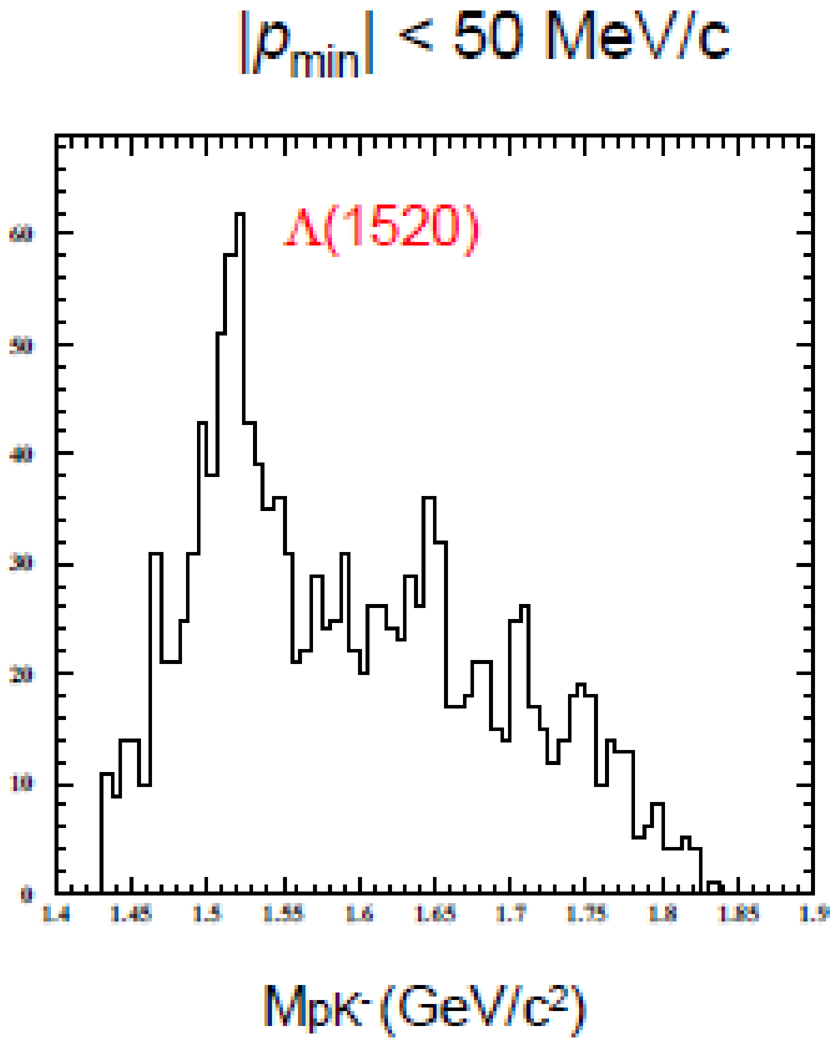
P09-LoI: Exotic Hadrons with S=+1 and Rare Decay K+→π+νν wit
Low-p K Beam (Nakano)
P19: Search for Θ+ Pentaquark in π-p → K-X Reactions (Naruki)

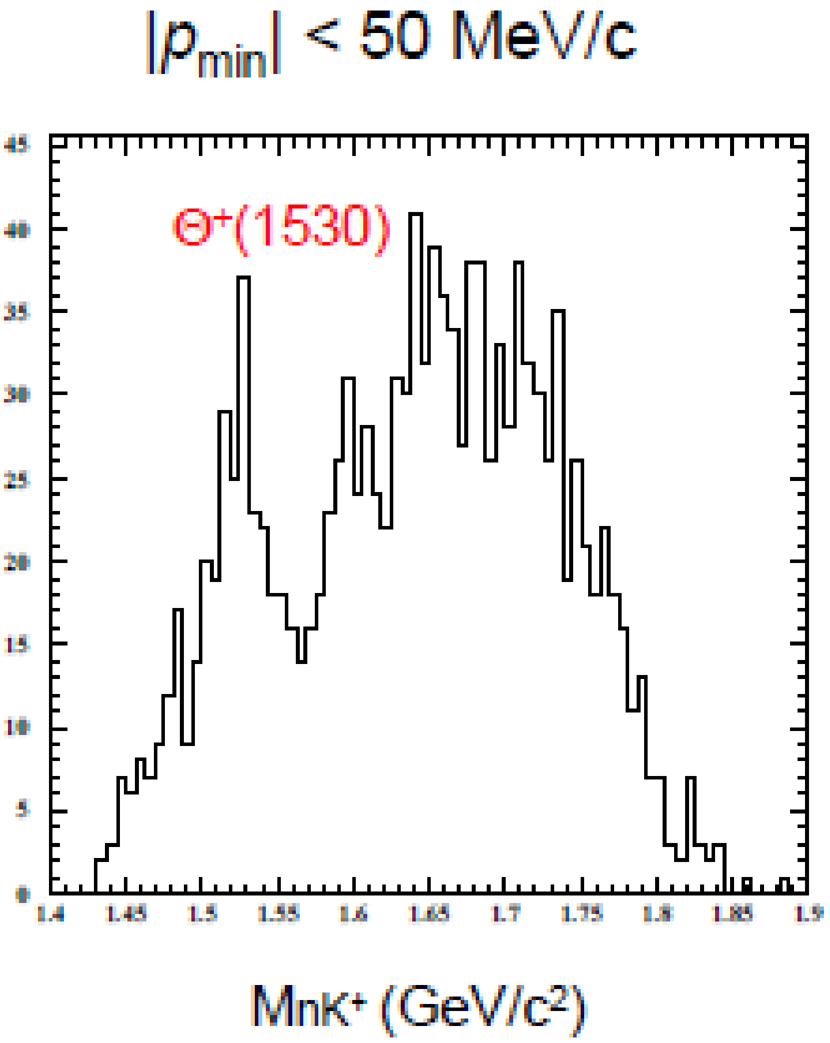
- マルチ (>3) クォークハドロンは存在する ！
  Charged chamonium-like state: Z(4430) (c cbar q qbar)
  Kbar N bound state: Λ(1405) (Dynamically generated res.)
  Penta Quark: Θ^+(1530)

- **LEPS** での **Penta quark** シグナルはどうやっても消えそうにない
  - 超前方のみに生成される（広がった状態か？）
  - 量子数は？
  - 格子 QCD → 散乱状態との区別の難しさ（境界条件 + Lattice size)
  - 狭い幅 → 角運動量効果？

> * **SPring8** 以外での **Penta Quark** の確認が不可欠
> * 理論的に質量と幅を説明するのは困難だが、
> あると信じて分析を進める価値が十分にあるだろう！

Penta Quark @ LEPS





Nakano

Summary

- **J-PARC の原子核・ハドロン物理**
  - バリオン多体系 (ハイパー核)
    + バリオン中間子多体系 (中間子核、核内中間子)
    + バリオン・中間子共鳴 (Λ(1405) などを含む)
    + マルチ・クォーク系 (ペンタ・クォーク、バリオン共鳴、....)
    + ハドロンの構造 (構造関数等 ← 触れられませんでした)
    = 「クォーク多体系」の広範な研究
  - 様々な観測量によるクォーク多体系の性質の解明
    = ハドロン物理学の王道
- **発見 (Discovery) + 実験・理論手法の開発 (Development) を通じて、高密度物質へ (Dense QCD)**
  - 理論 :Chiral Dynamics (主として中間子 , E-dep. pot. from loop) の手法とバリオン多体系の手法 (SR / tensor correlation を取り入れた多胎問題) の融合、格子 QCD での共鳴、多核子吸収、連続スペクトルからポテンシャルの制限、...
  - 実験 → 万博さんにまかせます。

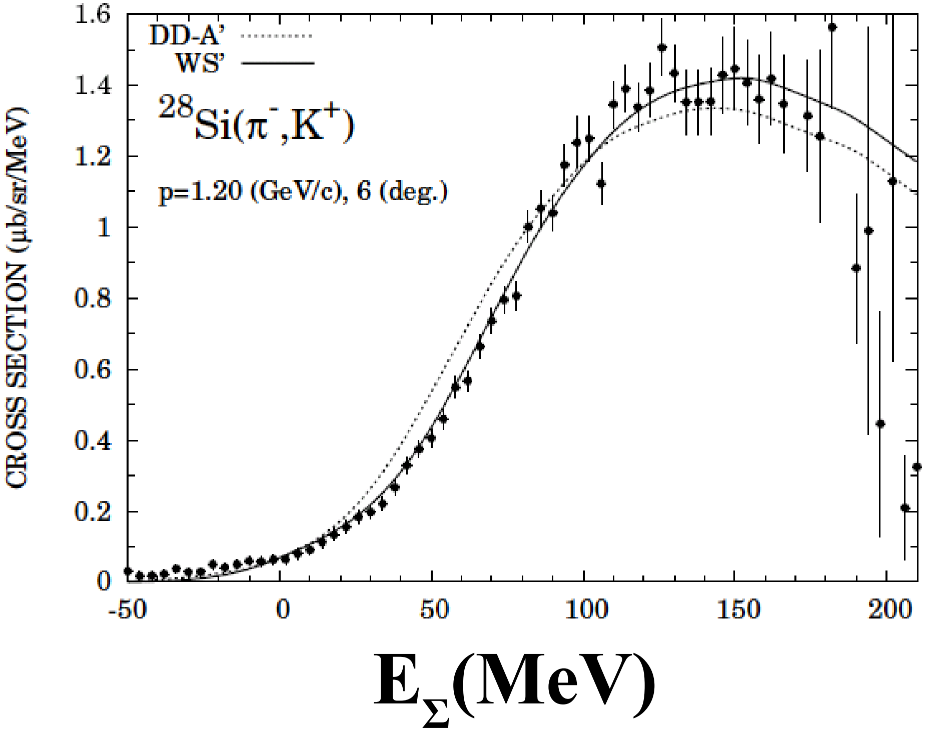
Thank you !

Backup

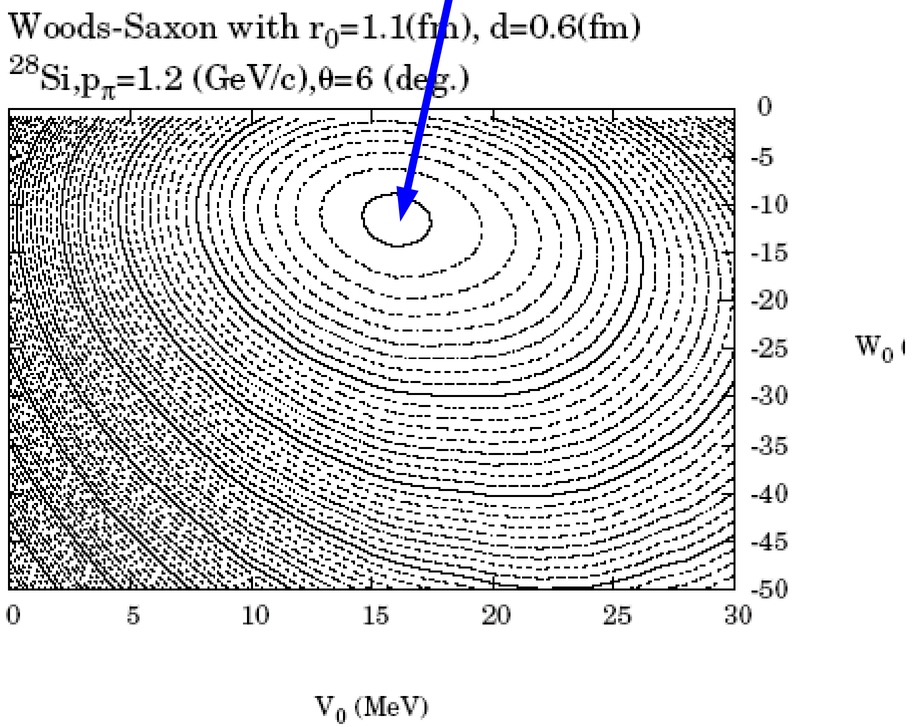
Σ Potential in Nuclear Matter

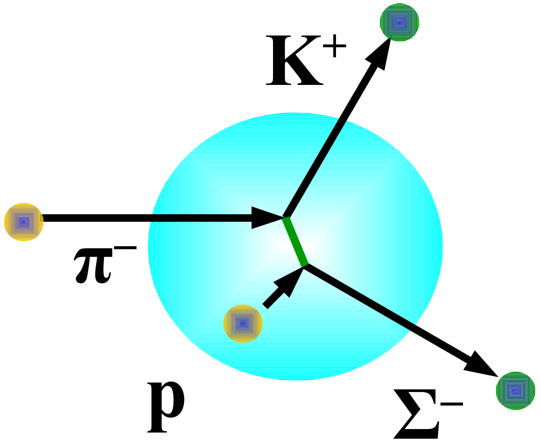
$$\frac{d^2\sigma}{d\,E_K\,d\,\Omega_K}$$

Maekawa, Tsubakihara, AO, EPJA 33(2007),269.
Maekawa, Tsubakihara, Matsumiya, AO, in preparation.



$U_\Sigma(\rho_0) \sim +15$ MeV –i 10 MeV
with Woods-Saxon potential,
no Atomic shift fit

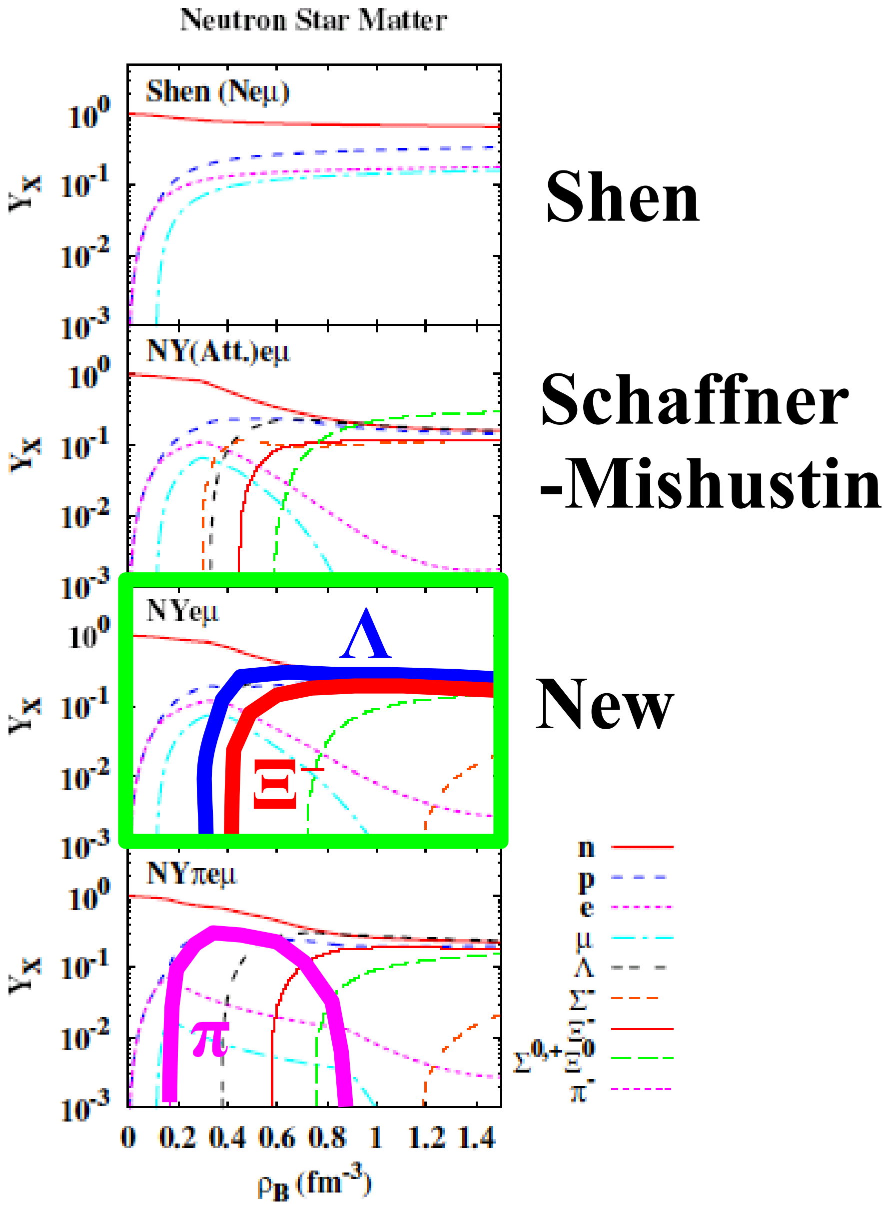


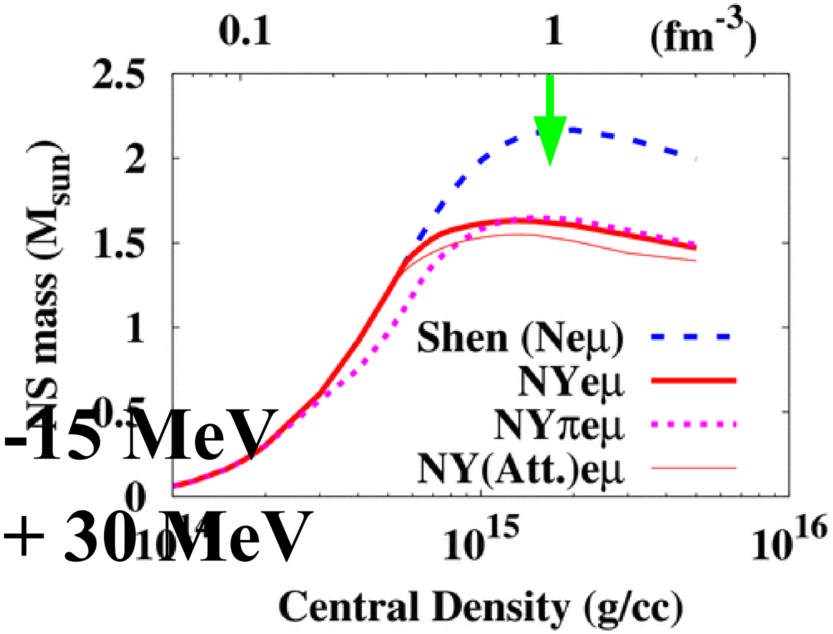


Neutron Star

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, 2008

- **Hyperon Effect is DRASTIC**
  - **Mmax=2.1 Msun → 1.56 Msun**
  - **Composition $Y_\Lambda \sim Y_n$**
  - **Large fraction of Ξ**
- **Thermal (free) pions can admix at $\rho > 1.5\ \rho_0$**





U_Ξ = -15 MeV

U_Σ = + 30 MeV