Hadron physics & Astrophysics

From Exotic Hadron to Neutron Star Matter EOS

Hadron Physics Symp., Apr.17-19, Nagoya, Japan

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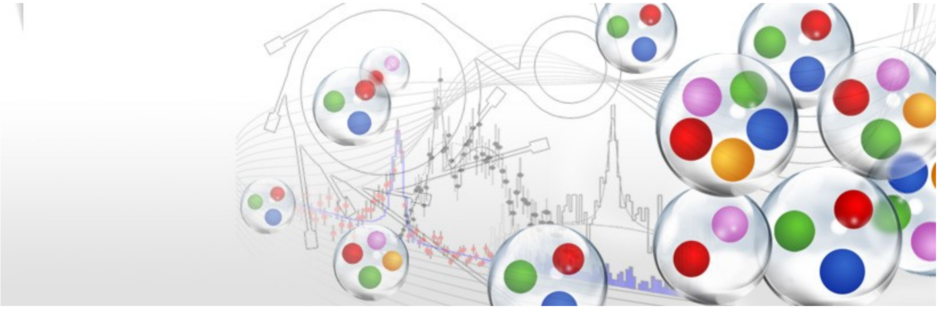
Grant-in-Aid for Innovative Areas

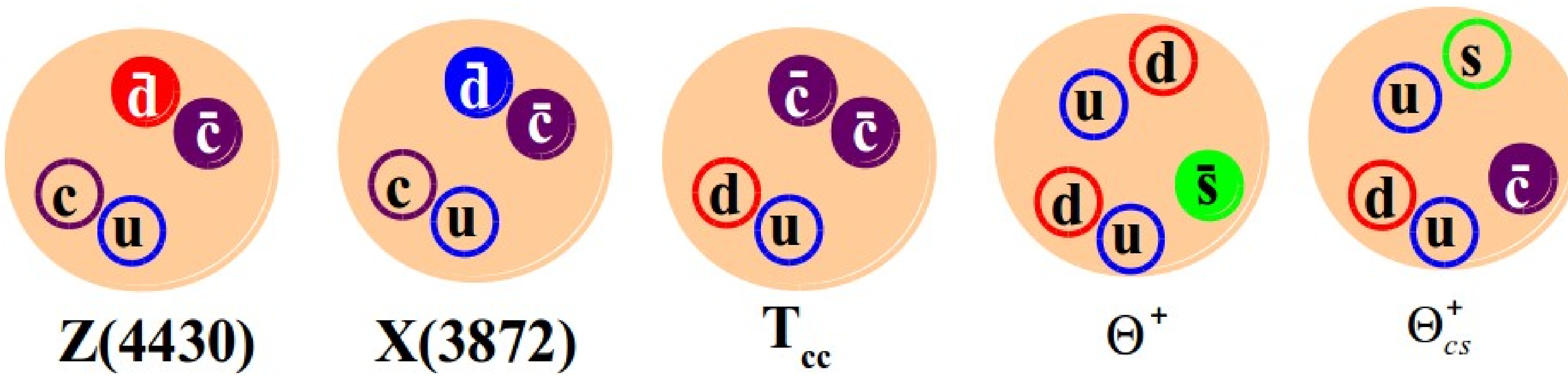
- New Hadron (2009-2014, T. Iijima)



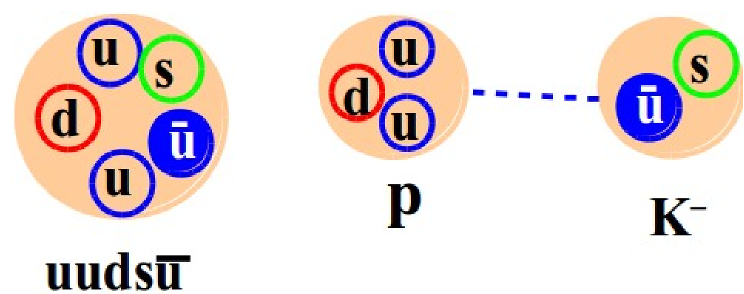
- Neutron Star Matter (2012-2017, H.Tamura)

New Hadrons

- Renaissance of hadron physics



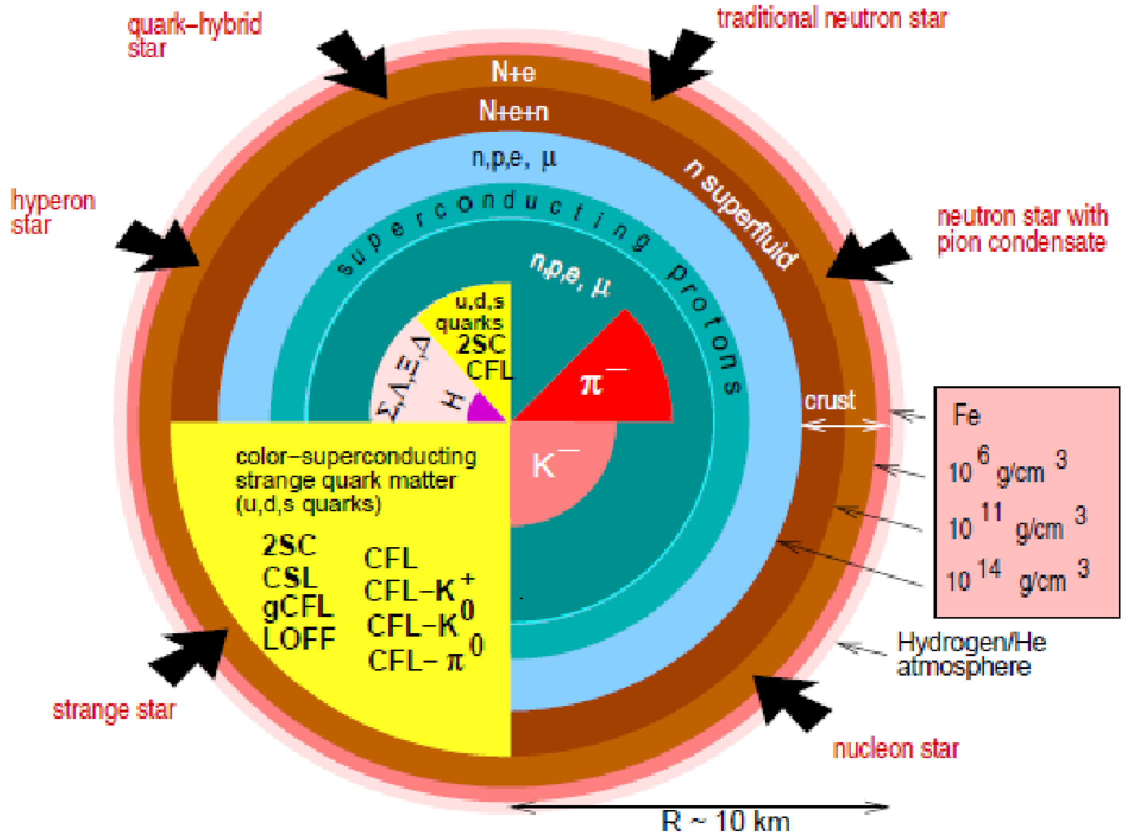
- Multi-quark state
  or Hadronic Molecule ?



Key quantity = Hadron size (interaction range)

Neutron Star Matter

- Cold, dense, charge neutral
- Constituents
  n, p, e, μ,
  Y, π, K,
  q, di-quark, ...

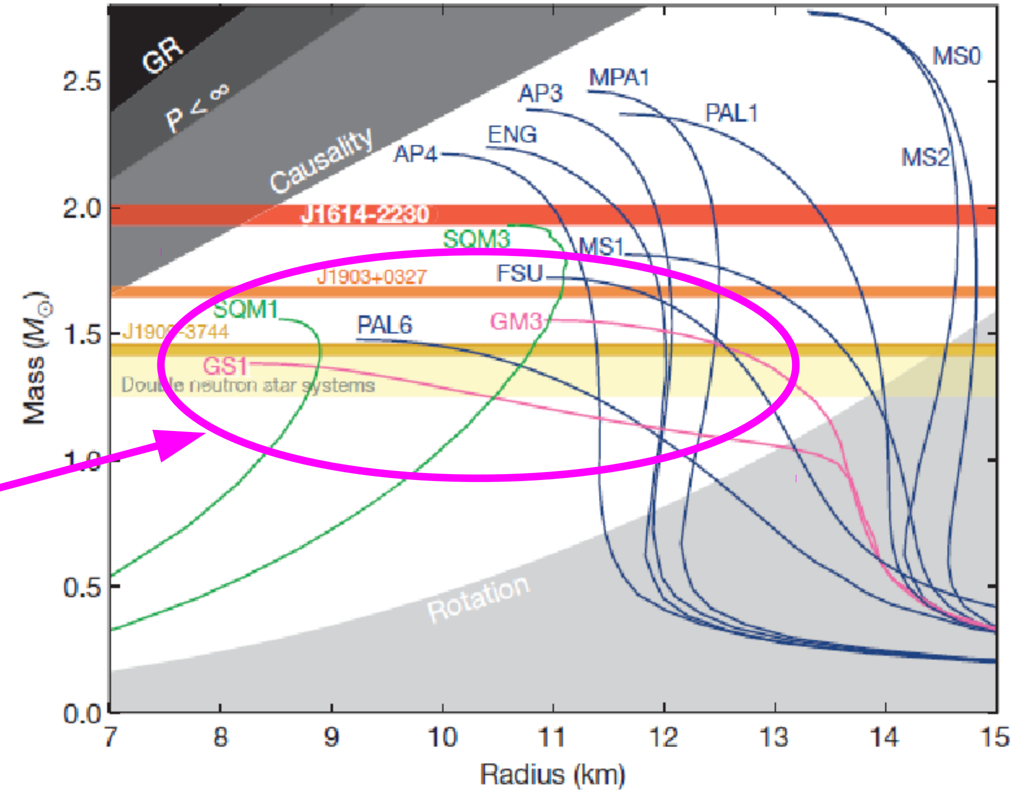


F. Weber, Prog. Part. Nucl. Phys. 54 ('05) 193

Can we determine int. btw constituents ?

Discovery of Massive Neutron Stars

- M_{NS}=1.97±0.04 M_{sun} measured using Shapiro delay (GR effect).
- EOSs w/ strange hadrons are ruled out, while Lab. exp. suggest their existence in NS.

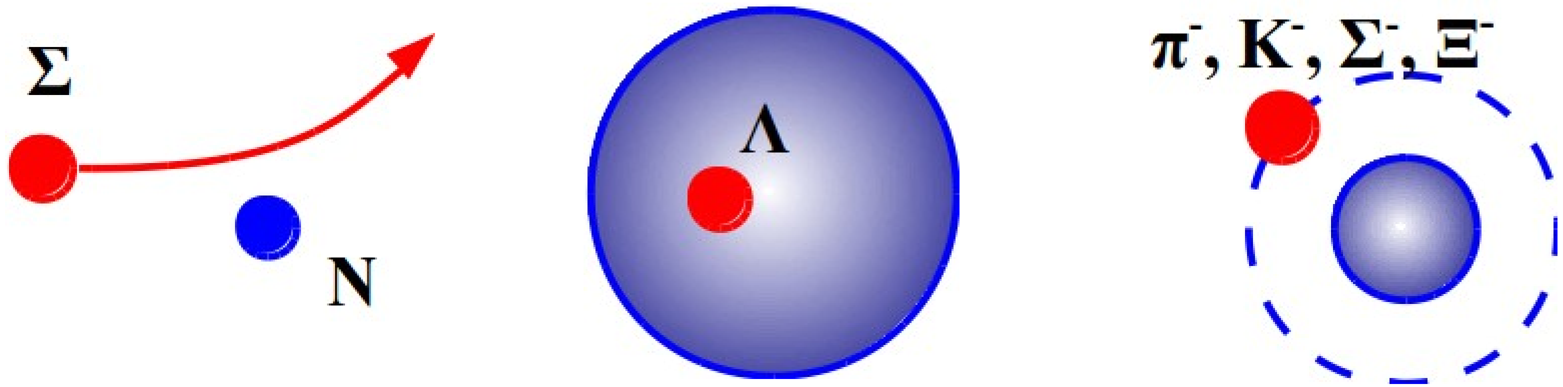


Demorest et al., Nature 467 (2010) 1081.

Massive Neutron Star Puzzle

Interactions btw short-lived hadrons

- Scattering, Nuclear bound state, Atomic shift



NS matter grant

- Correlations from heavy-ion collisions
- Exotic hadron spectroscopy

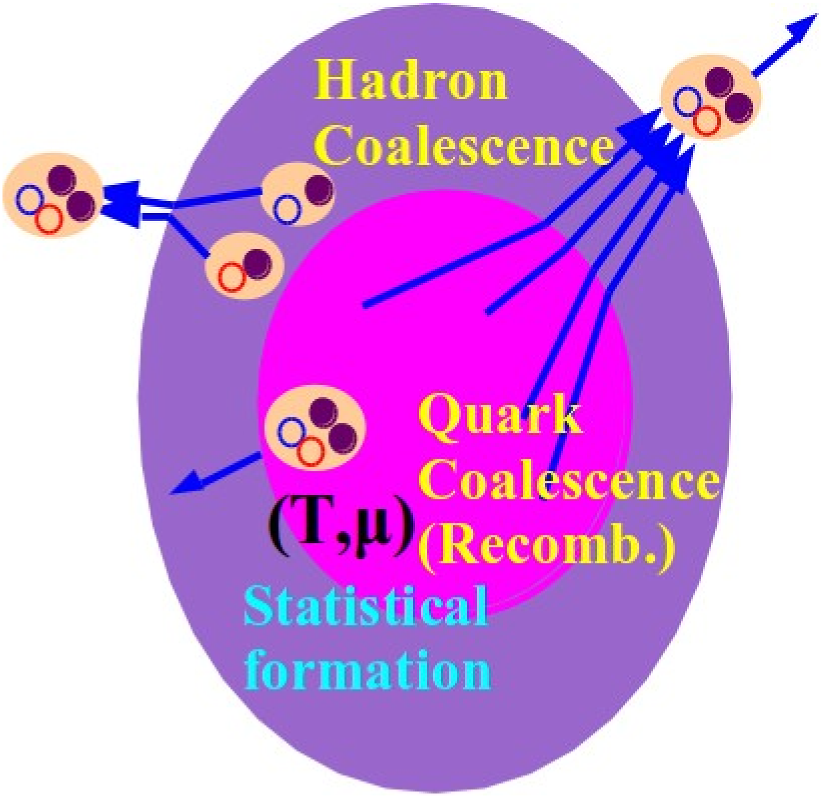
Exotic hadron is important to access hh int.

Contents

- Introduction
- Exotic hadrons
  and hadron-hadron interaction
  - Exotic hadrons from heavy-ion collisions (S.H.Lee)
  - Hadron-hadron interaction from heavy-ion collisions
- Impact on Neutron Star Matter EOS
  - Hyperonic EOS after 2 Msun NS discovery
  - “Universal” 3-body repulsion
- Summary

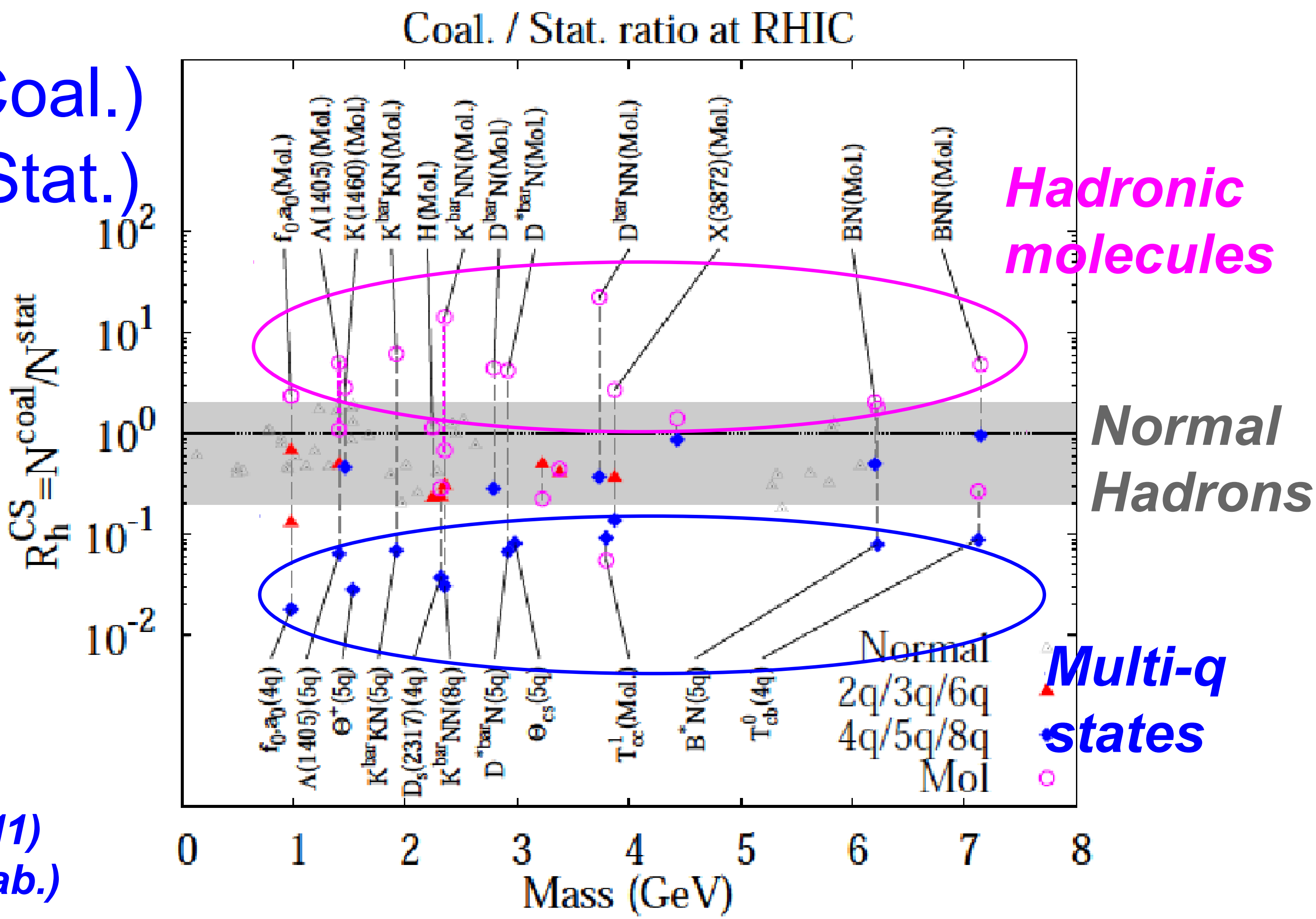
Exotic hadrons from Heavy-Ion Collisions

- HIC = Hadron factory
- Formation mechanism
  = Statistical ,
  Coalescence,
  Fragmentation.
- Yield(stat.)~Yield(Coal.) for normal hadrons.
- What happens for exotic hadrons ?



Exotic hadrons from Heavy-Ion Collisions

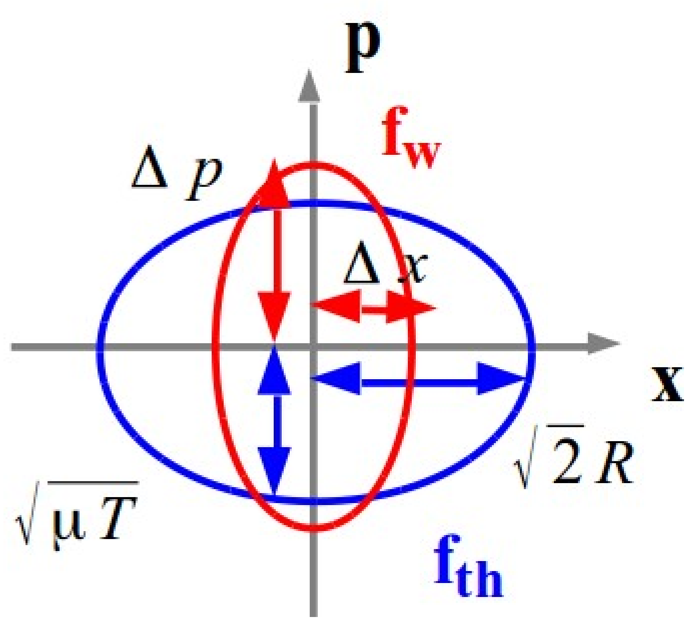
Yield(Coal.) / Yield (Stat.)



Cho et al. ('11) (ExHIC Collab.)

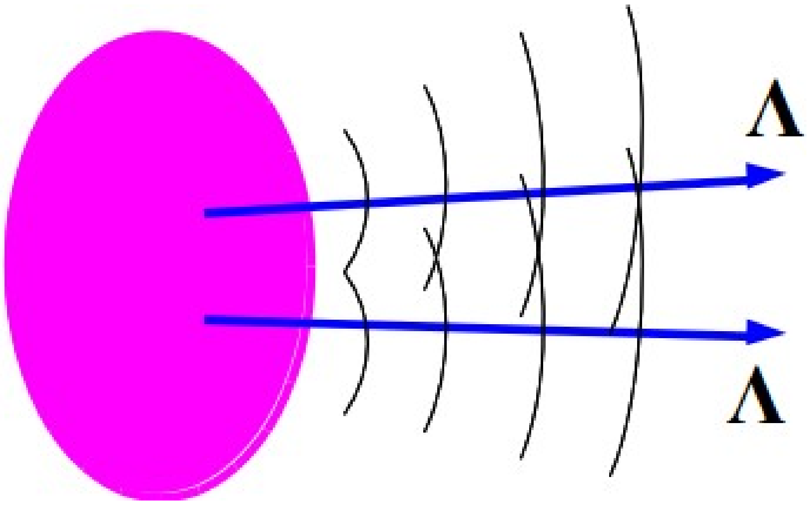
Hadron size and production yield

- Yield(Coal.) $\propto \int f_{th}$(const.) x f_W (intrinsic)
  f = phase space dist. fn. (Wigner fn.)
  → Larger yield for similar shape of f
  in phase space.
- Example:
  T=170 MeV,
  red. mass=500 MeV
  source size= 5 fm
  → optimal hω ~ 16 MeV
  (<< 300-500 MeV)

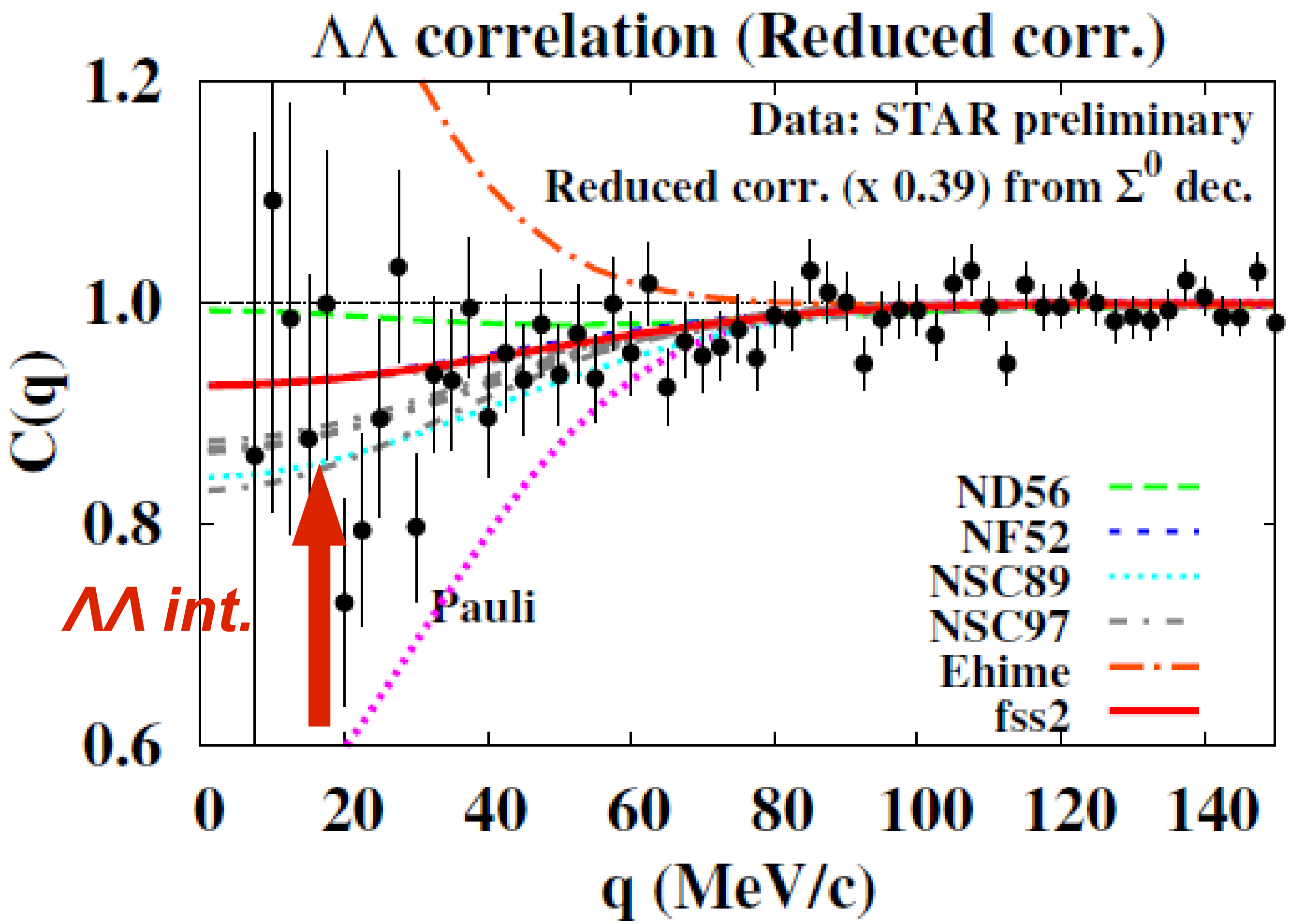


Hadron-Hadron correlation in HIC

- Correlation func. ~ ∫ Source x $|\mathrm{w.f.}|^2$
  → If source is known, corr. fn. tells us w.f. or interaction.
  Bauer, Gelbke, Pratt ('92); Lednicky ('09).
- ΛΛ correlation is measured in (K^-,K^+) reaction
  C.J.Yoon et al. (KEK-E522)('07)
  J.K.Ahn et al. (KEK-E224)
- STAR measured ΛΛ correlation at RHIC
  N. Shah et al.('12)



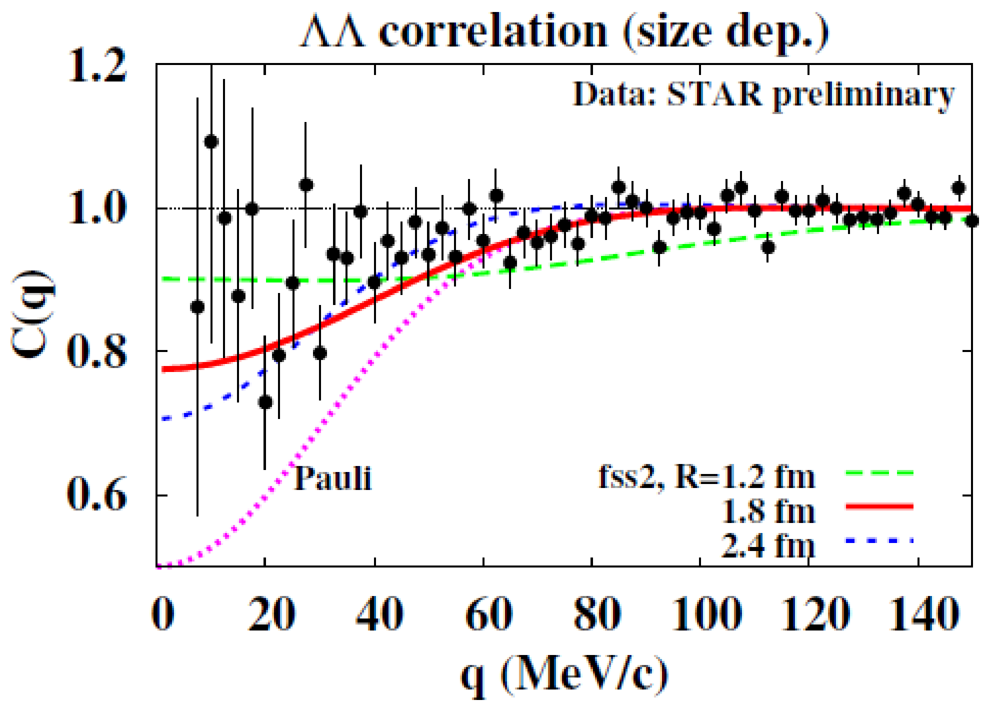
ΛΛ correlation at RHIC



Data (STAR prelim.): N. Shah et al.('12), Cal.: AO for ExHIC ('13)

ΛΛ interaction and correlation

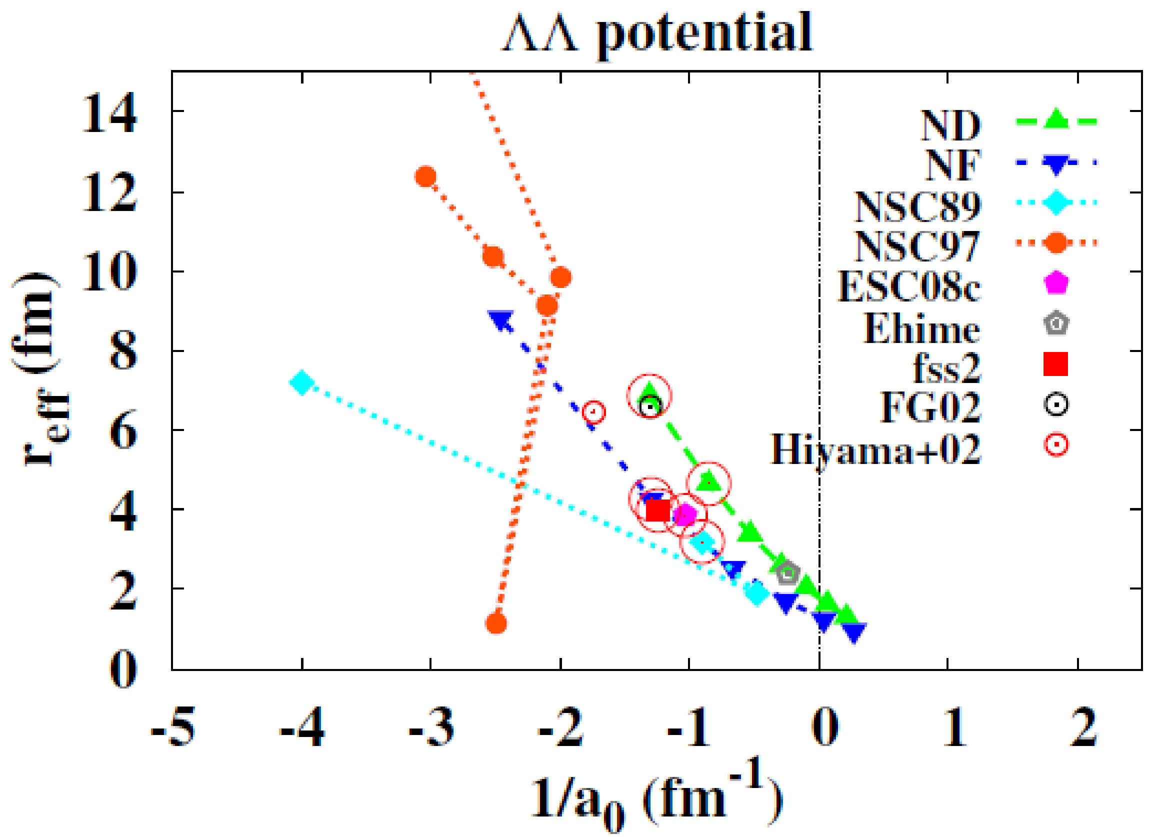
- ΛΛ int.
  - Nijmegen models
    Rijken et al.
  - quark model (fss2)
    Fujiwara et al. ('01)
  - Nagara fit
    Filikhin, Gal ('02)
    Hiyama et al.('02)
- Source models
  - sph. static source
  - cylindrical source w/ flow



AO et al. (ExHIC Collab.), NPA914 ('13), 377 [arXiv:1301.7261 [nucl-th]].

Analysis of updated STAR data is in progress and will be reported in K. Morita, AO, T. Furumoto (in prep.)

Preferred ΛΛ interaction



Allowed region from updated STAR data will be reported in
K. Morita, AO, T. Furumoto (in prep.)

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  - "Universal" 3-body repulsion
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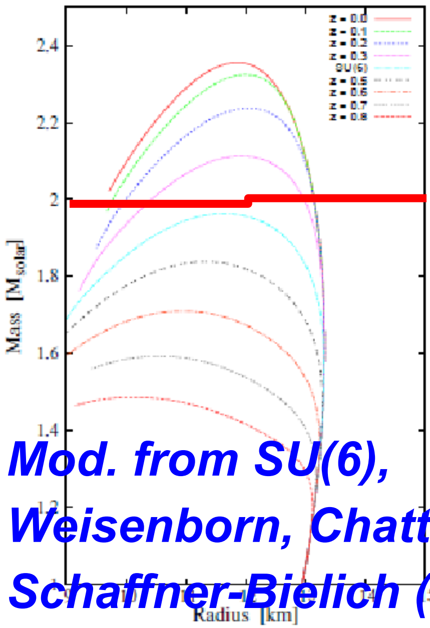
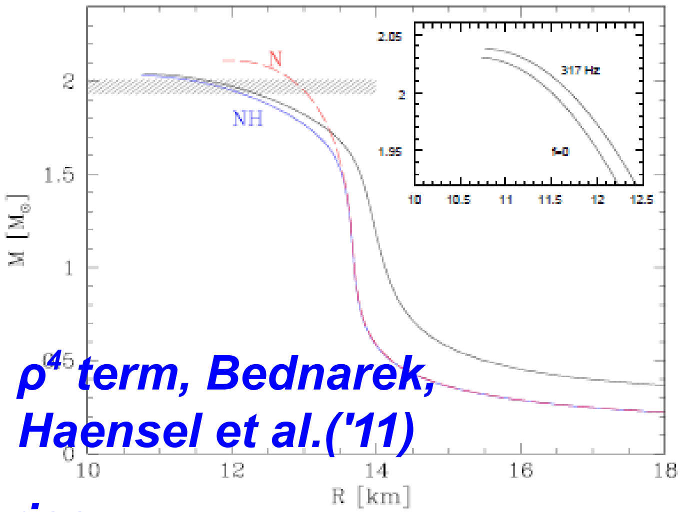
NS matter EOS with hyperons

- "Ruled-out" hyperonic EOS = Naive RMF
  Glendenning, Moszkowski ('91)
  - Relativistic Mean Field (RMF) models
  - SU(6) coupling (~ quark counting) $g_{\sigma\Lambda} = \frac{2}{3}\ g_{\sigma N}$
  - No $s\bar{s}$ mesons
- Proposed prescription after 2 Msun NS
  - Modify coupling constant from SU(6) value
    Weisenborn et al. ('11); Tsubakihara, AO, Harada ('13)
  - Introducing three-body repulsion
    Bednarek, et al.('11); Miyatsu, Yamamuro, Nakazato ('13)
  - Crossover transition to quark matter
    Masuda, Hatsuda, Takatsuka ('12)

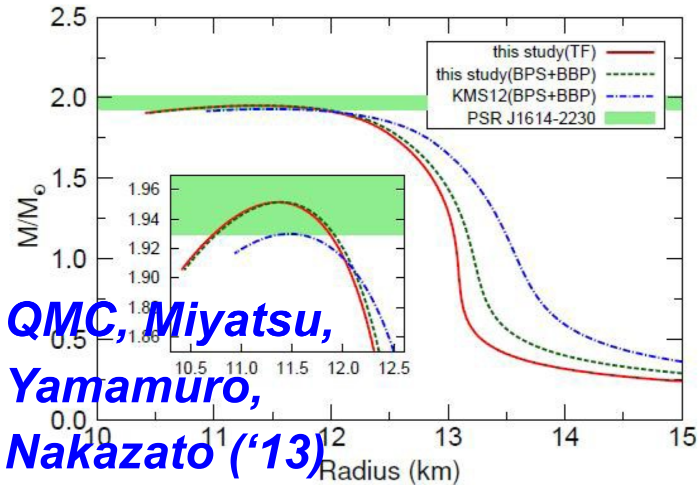
NS matter EOS with hyperons



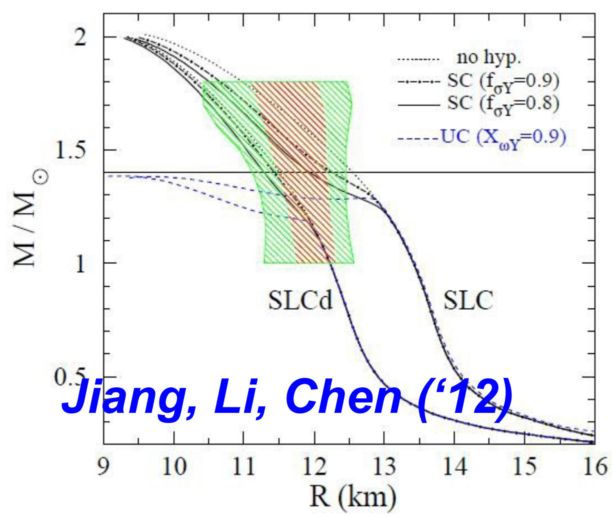
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



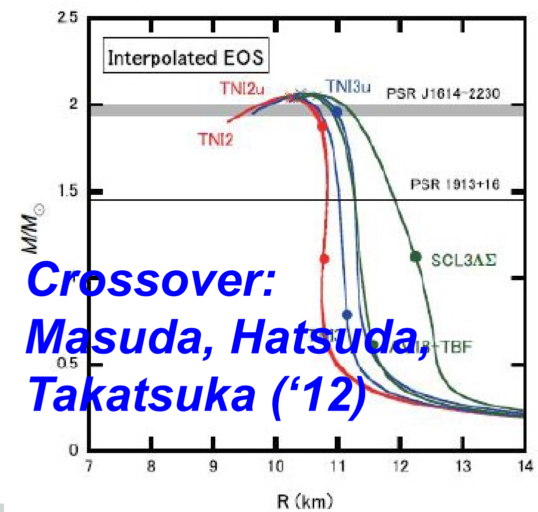
ρ^4 term, Bednarek, Haensel et al.('11)



QMC, Miyatsu, Yamamuro, Nakazato ('13)

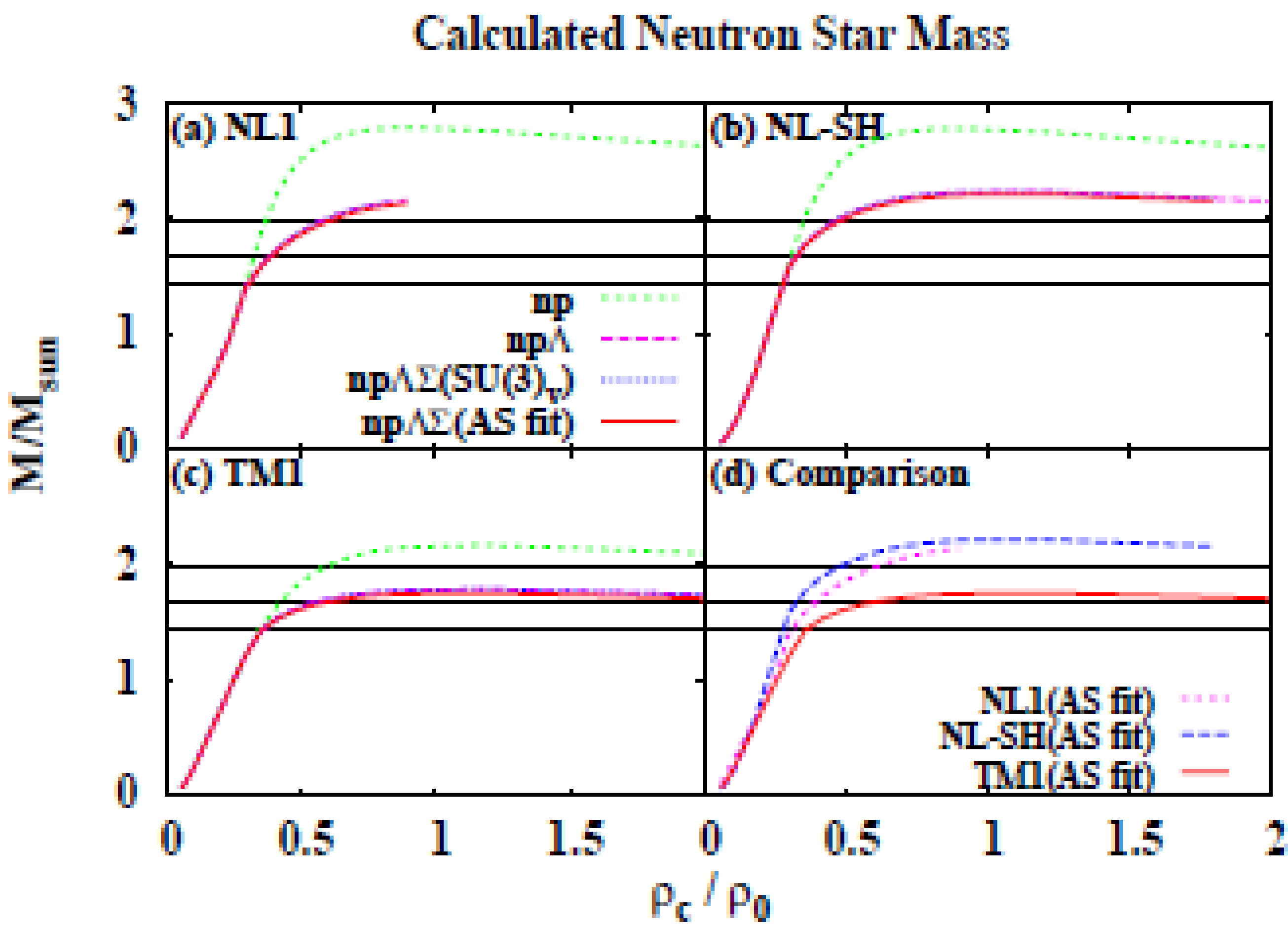


Jiang, Li, Chen ('12)



Crossover: Masuda, Hatsuda, Takatsuka ('12)

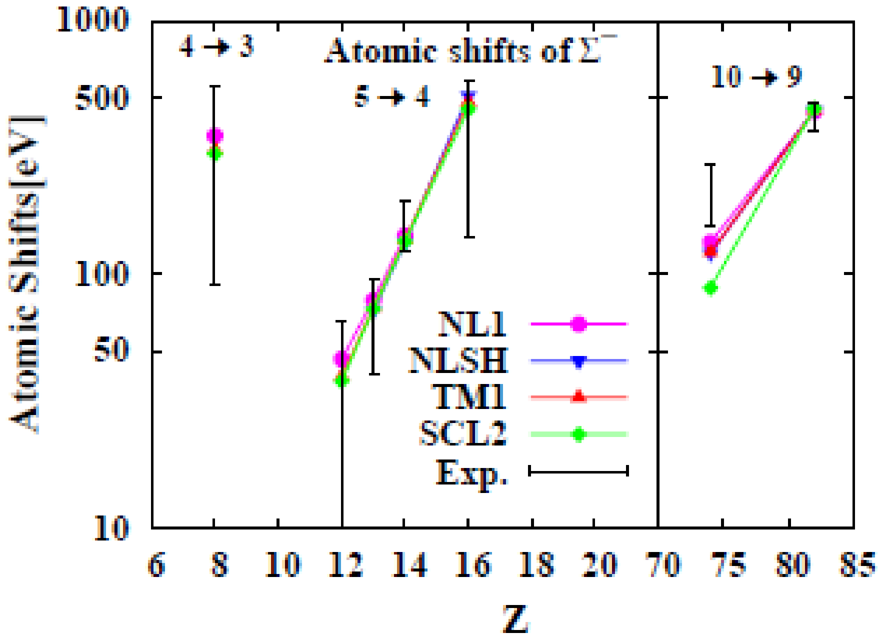
NS matter EOS with hyperons



Non-linear term dep. +Atomic shift fit:
Tsubakihara, AO, Harada, arXiv:14020979

Vector coupling in RMF

- Σ- atomic shift
  - Measured for isospin symmetric (O, Si) and asymmetric (W, Pb) nuclei.
  - gρΣ need to be much smaller than SU(6).
    $g_{\rho\Sigma}$ (SU(6))=2 $g_{\rho N}$
    $g_{\rho\Sigma}$ (AS)=(0.3-0.4)$g_{\rho N}$
    Mares, Friedman, Gal, Jennnings ('95)



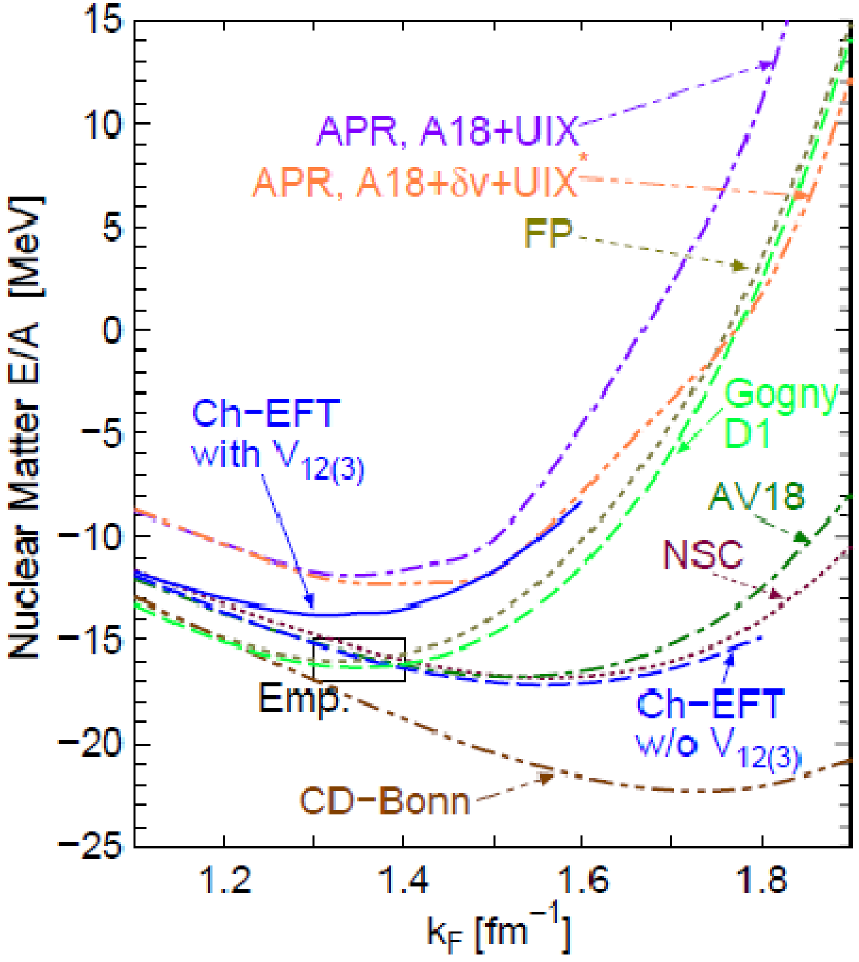
Mesons in RMF should be taken as effective field

Tsubakihara, AO, Harada, arXiv:14020979

Ch-EFT EOS

- Phen. models need inputs from
  - Experimental Data

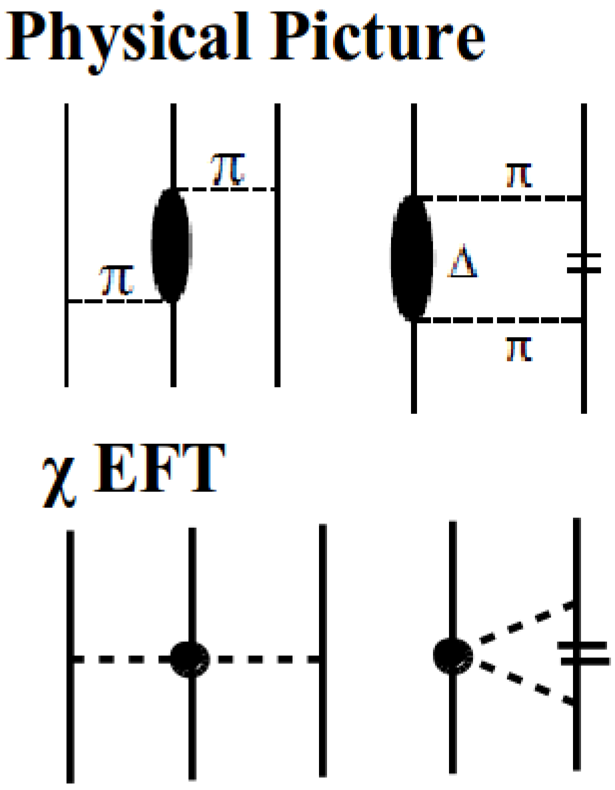
  and/or
  - Microscopic (Ab initio) Calc.
- Recent Ch-EFT EOS is promising !
  - NN (N3LO)+3NF(N2LO) Kohno ('13)



M. Kohno, PRC 88 ('13) 064005

"Universal" mechanism of "Three-body" repulsion

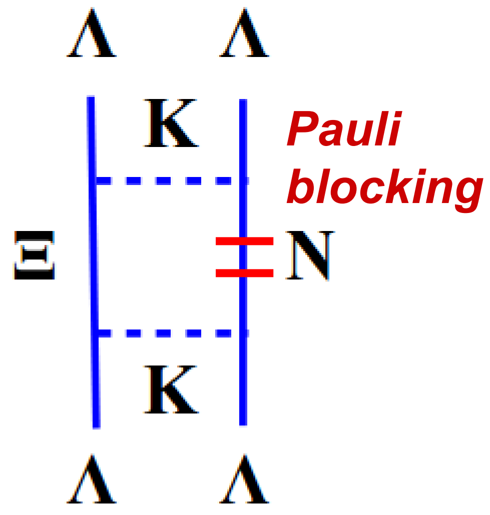
- "σ"-exchange ~ two pion exch. w/ res.
  - "Universal" 3-body repulsion is necessary
    Nishizaki, Takatsuka, Yamamoto ('02)
  - Large attraction from two pion exchange is suppressed by the Pauli blocking in the intermediate stage.
    → Three-body repulsion



"Universal" 3BR = Reduced "σ" exch. pot. ?

ΛΛ interaction in vacuum and in medium

- ΛΛ interaction in vacuum may be accessible
  - Correlation from HIC
  - Lattice QCD calc. ***HAL QCD ('11) & NPLQCD ('11)***
- ΛΛ interaction could be different in vacuum and in medium
  - a_0(~ best fit, fss2) = 0.82 fm
    Fujiwara et al. ('01)
  - a_0(Nagara fit) = 0.575 fm
    Hiyama et al. ('02)
- Pauli blocking in the Q-space ?
  - ΛΛ-ΞN couples in vacuum
  - Coupling is suppressed in $^{6}_{\Lambda\Lambda}$He



Summary

- Hadron size and interaction between short-lived hadrons would be accessible via spectroscopy, yield, and correlation.
    - ExHIC conjecture: Larger yield of multi-q. states in e^+e^- and pA collisions.
- NS matter EOS with hyperons can support 2 Msun NS by introducing phen. parameters.
    - Need exp. data and ab initio calc.
      J-PARC exp. / Lattice BB and BBB int. / Ch-EFT
    - Comparison of ΛΛ nuclei and ΛΛ corr. in HIC may be useful to pin down YYN three-body repulsion.

Let's keep in touch !

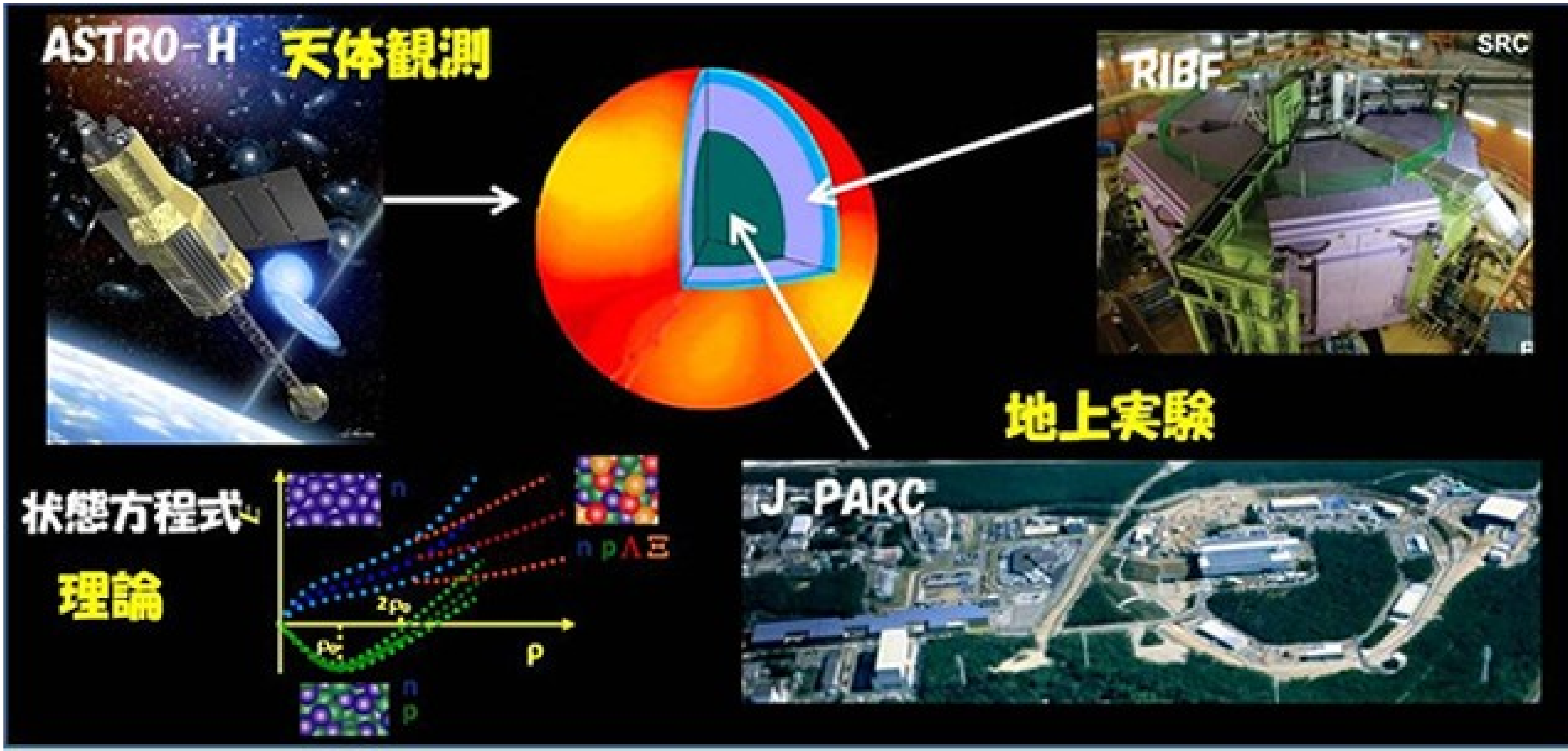
Future works & Remaining problems

- Even in phen. EOS with three-body couping, consistent understanding of

  K, E_{sym}, L, M_{max}, U_Y, …

  are not obtained.
  - How can we incorporate ab initio results in phen. treatment ?
- ΛΛ correlation is still problematic.
  - Obtained source size seems to be very small (Homogeneity length, rather than source size).


Neutron Star Matter
実験と観測で解き明かす中性子星の核物質
Nuclear matter in neutron stars investigated by experiments and astronomical observations


ASTRO-H
天体観測
RIBF
SRC
地上実験
J-PARC
状態方程式
理論
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n
p