# *Three Baryon Interaction in the Quark Cluster Model*

*– 3B Interaction from Determinant Interaction of Quarks as an example –*

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**Seminar at Hokkaido U., Nov. 30, 2016**

*AO, K. Kashiwa, K. Morita, arXiv:1610.06306*

# A. Ohnishi (CV)

- CV
  - Born in Kobe ('64), B. Sc. '87, M. Sc. '89, D. Sc. '92 (Kyoto Univ.)
  - JSPS fellow @ RCNP ('92-'93), Hokkaido U., ('93-'08), YITP ('08-)

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  - Hyperon Puzzle
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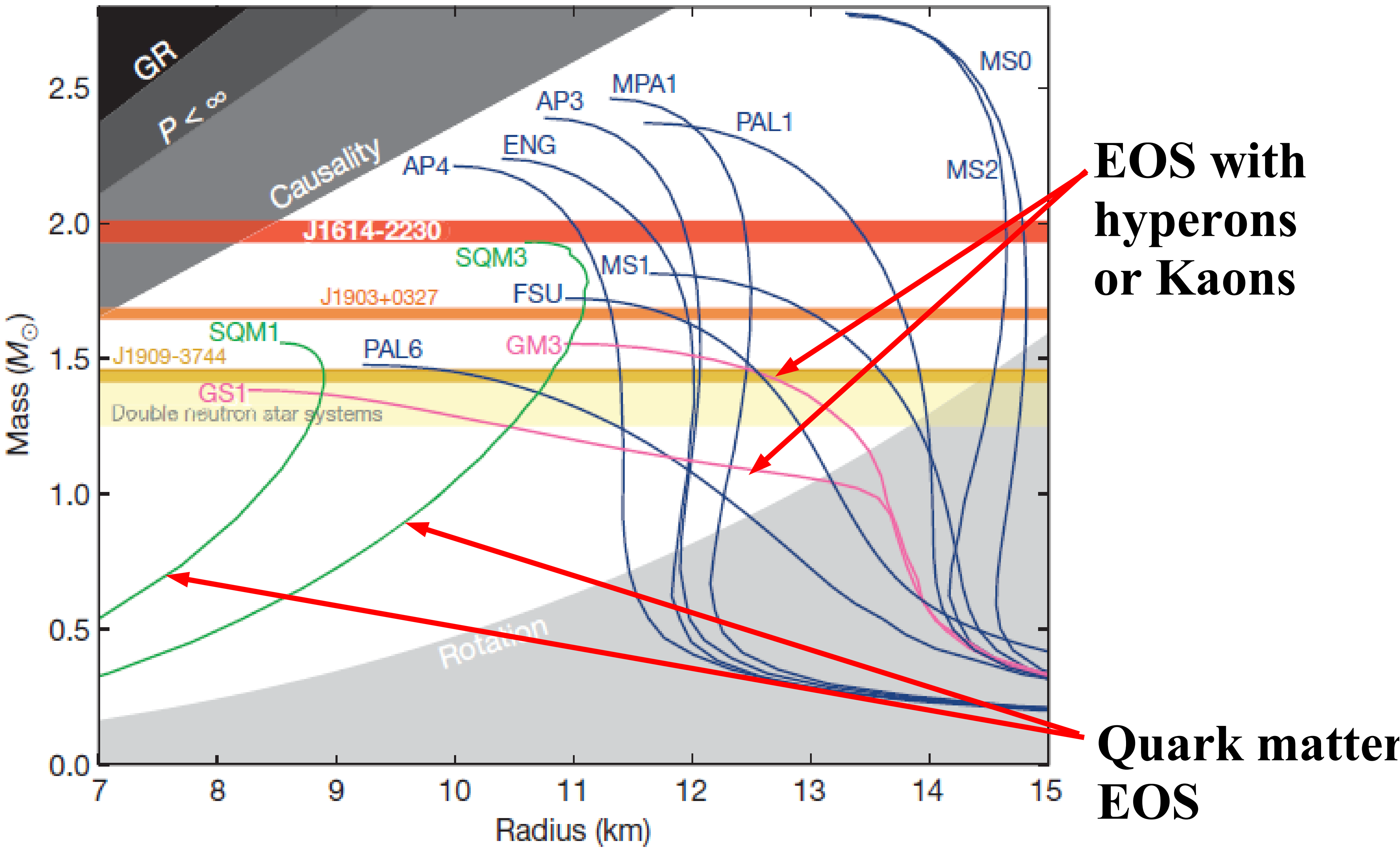
# *Hyperon Puzzle (or Hyperon Crisis)*

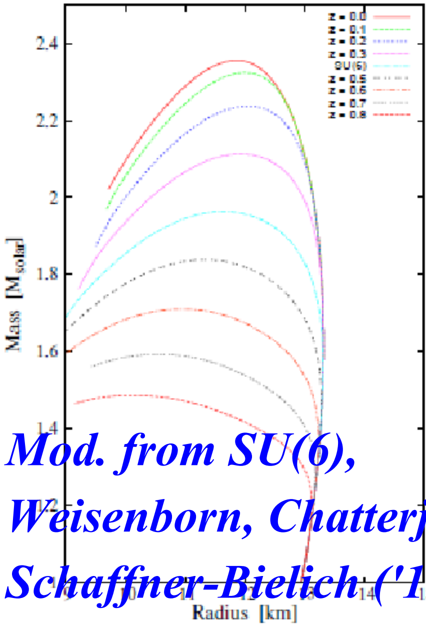
***Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).***



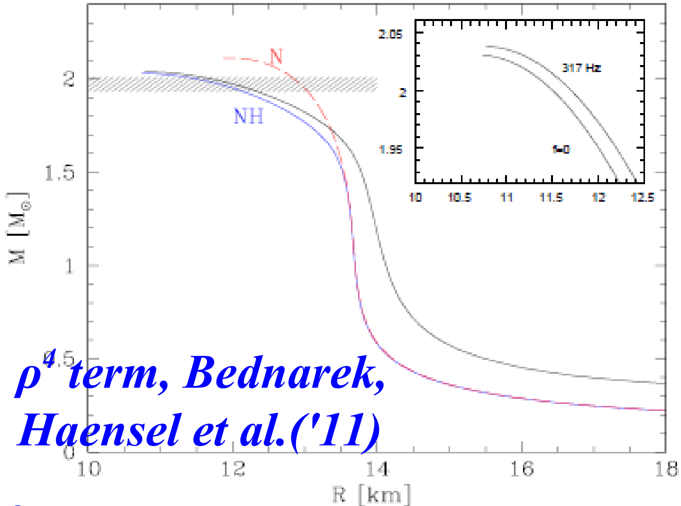
# Proposed Solutions

- **Hyperonic EOS cannot support massive NS ($M \sim 2\ M_\odot$).**
  *Demorest et al. (2010), Antoniadis et al. (2013)*
- **Proposed Solutions**
  - **Hyperonic Three-Body Force (or density dep. coupling)**
    *Bednarek et al. ('12), Jiang et al. ('12); Long et al. ('12); Yamamoto et al. ('14); Lonardoni et al. ('15); Tsubakihara et al. ('13), T. Miyatsu et al. ('13), …*
  - **Crossover Transition to Quark Matter**
    *Bonanno et al.('12); Masuda et al. ('13); Bejger et al.('16), …*
  - **Modified Gravity**
    *Astashenok et al. ('14)*
- **Three-nucleon interaction is known to be necessary.**
  **How can we determine YNN (+YYN, YYY) potential ?**

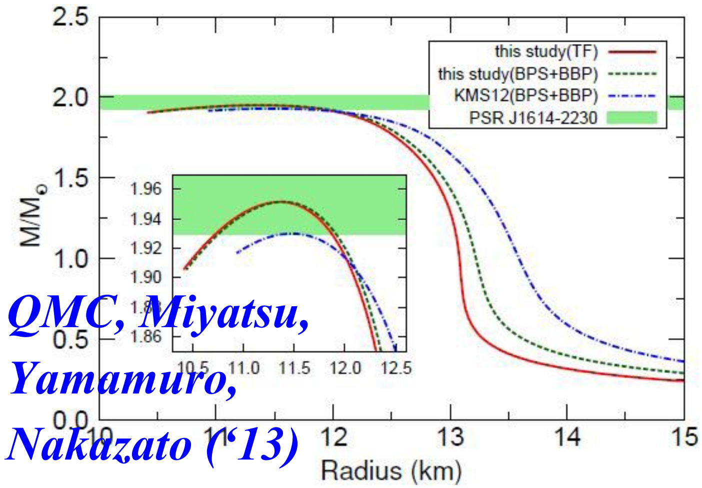
# *Massive Neutron Stars with Hyperons*



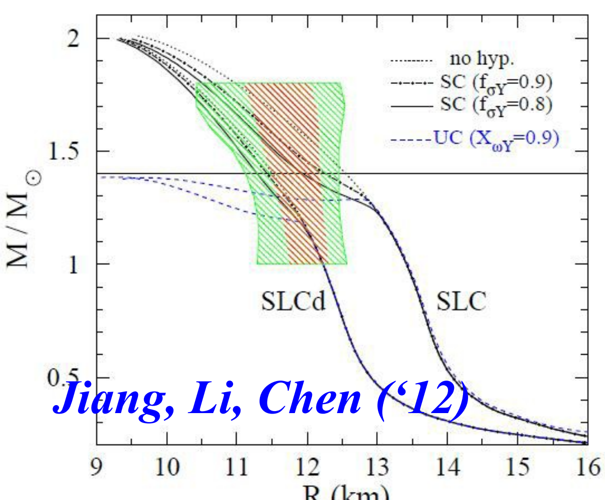

*Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)*



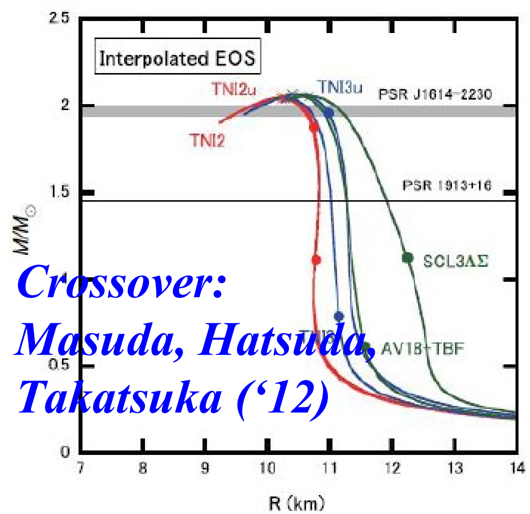

*$\rho^4$ term, Bednarek, Haensel et al.('11)*



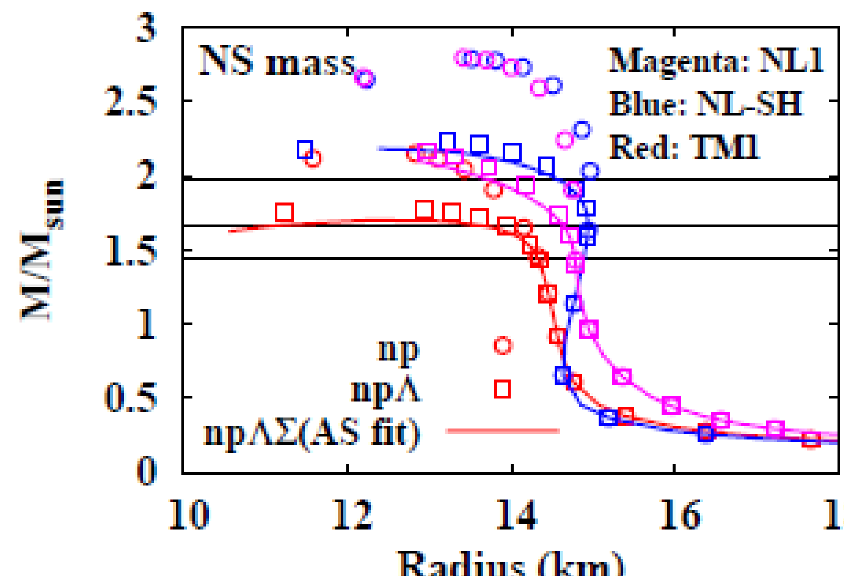

*QMC, Miyatsu, Yamamuro, Nakazato ('13)*




*Jiang, Li, Chen ('12)*



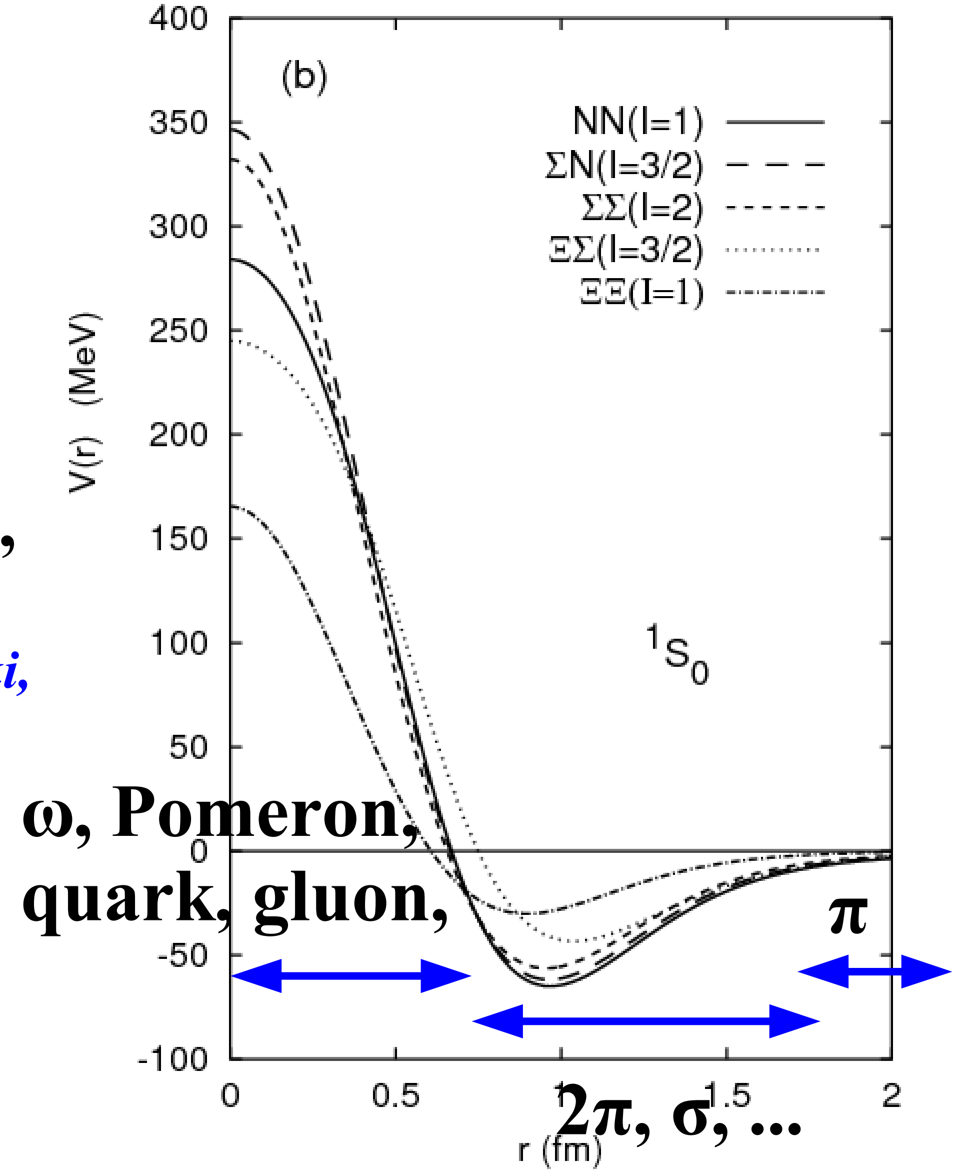

*Crossover: Masuda, Hatsuda, Takatsuka ('12)*




*Tsubakihara, Harada, AO, arXiv:1402.0979*

# Baryon-Baryon Force

- **Long-range (r>2 fm): π exch.**
- **Intermediate (r ~ 1 fm):**
  **multi π exch., boson exch., …**
- **Short range (r < 0.6 fm):**
  **vector boson exch.,**
  **Pomeron exch.,**
  **quark exclusion + one gluon exch.,**
  **…**
  *V.G. Neudachin, Yu.F. Smirnov, R. Tamagaki, PTP 58 ('77) 1072; M. Oka, K. Yazaki, PTP ('81)572.*

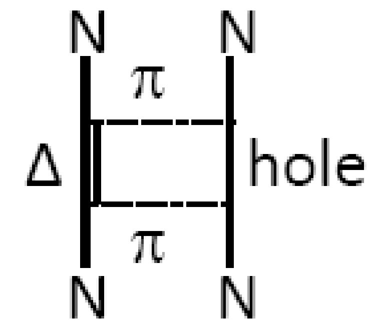


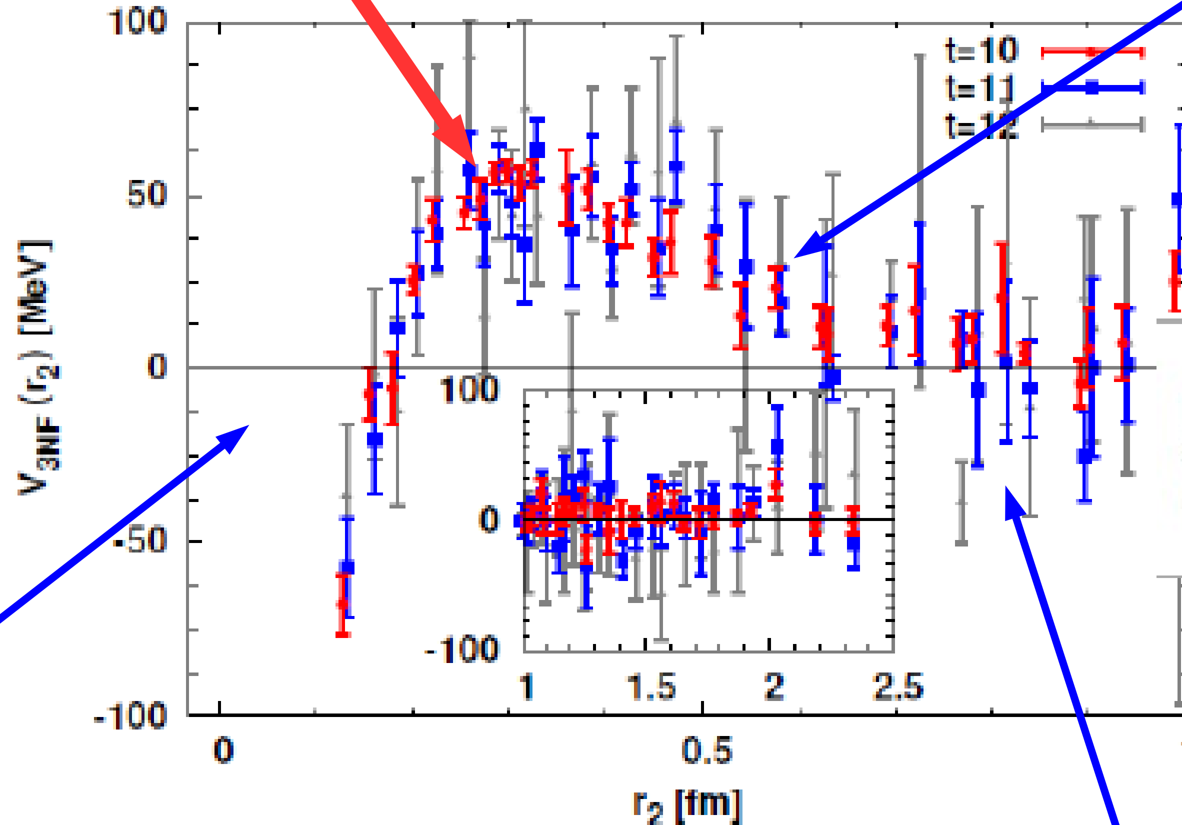

*Fujiwara, Suzuki, Nakamoto ('07)*

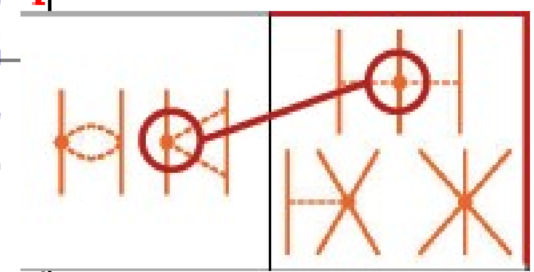
> ***Quark model description of 3B repulsion should be a promising approach !***

# *Three-Baryon force*

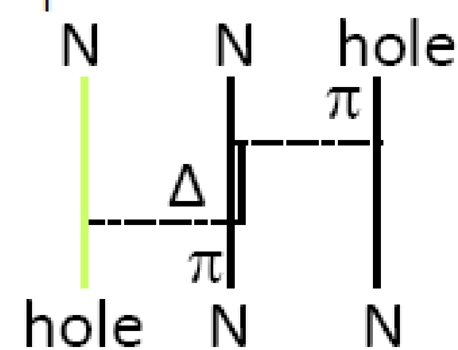
**What makes 3B repulsion at r ~ 0.5 fm ?**



**pQCD**



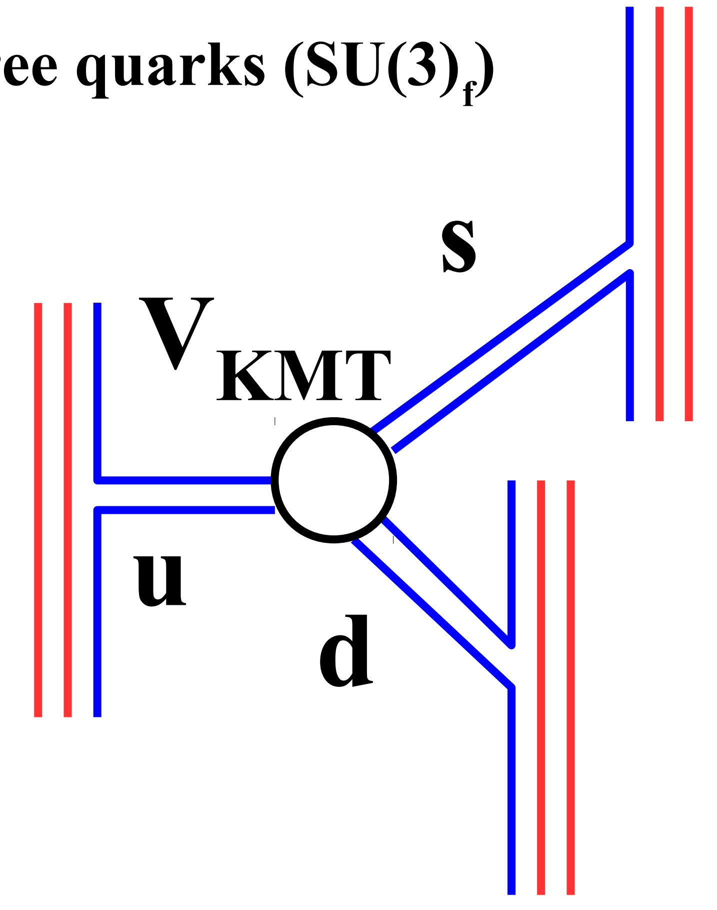

**Taken from NPCSM 2016 talks,**
**Doi (Wed), Kohno (Thu), Tews (Thu)**

# Kobayashi-Maskawa-'t Hooft (KMT) interaction

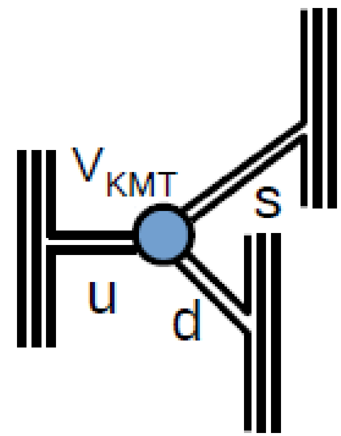
- **KMT interaction** *Kobayashi, Maskawa ('70), 't Hooft ('76)*

$$\mathcal{L}=g_D\ (\det\Phi+\mathrm{h.c.})\ ,\quad \Phi_{ij}=\bar{q}_j(1-\gamma_5)q_i$$

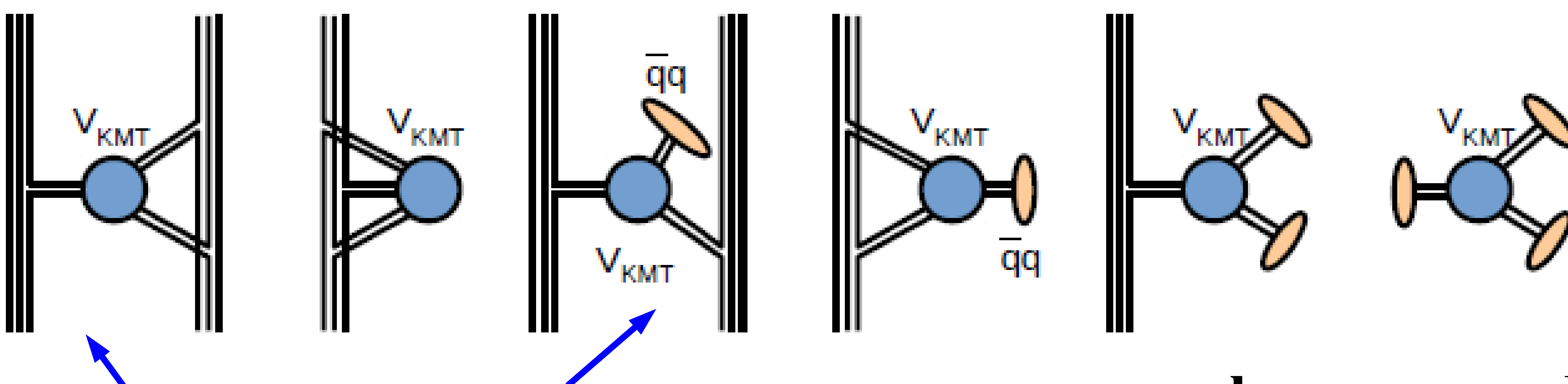
- **Determinant interaction in flavor for three quarks ($SU(3)_f$)**
- **Responsible for $U(1)_A$ anomaly**
  **η-η' mass diff.**
  **→ $g_D$ = – 9.29** *Hatsuda, Kunihiro ('94)*
  **– 12.36** *Rehberg, Klevanski, Hufner ('96)*
- **KMT interaction should generate**
  **2B and 3B interaction**
  **when hyperons are involved.**
- **Repulsive in ΛΛ system**
  **→ Pushes up H particle energy.**
  *Takeuchi, Oka ('91)*



# *Kobayashi-Maskawa-'t Hooft (KMT) interaction*




**3B force**
**(AO, Kashiwa, Morita)**




**Repulsion in ΛΛ int.**
**Takeuchi, Oka ('91)**

**quark mass, vac. E.**
**(Hatsuda, Kunihiro)**

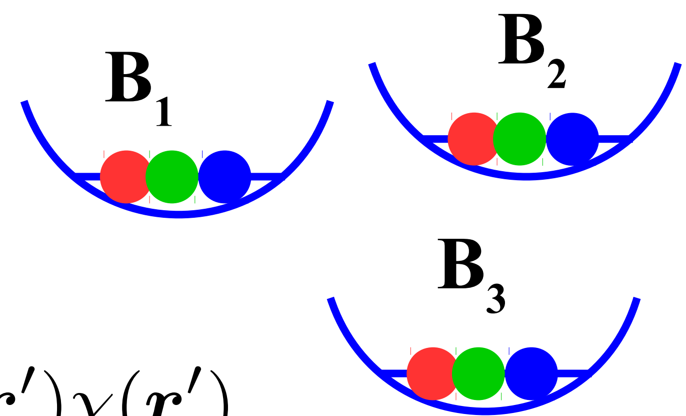
## *Does anomaly support massive NS ?*

# *Quark Cluster model*

- **Totally anti-symmetrized wave function of baryons**

$$|\Psi\rangle = \mathcal{A}|\chi_{12}B_1B_2\rangle$$

$$|\Psi\rangle = \mathcal{A}|\chi_{123}B_1B_2B_3\rangle$$




- **Resonating Group Method**

$$\int d\boldsymbol{r}' H(\boldsymbol{r},\boldsymbol{r}')\chi(\boldsymbol{r}') = E\int d\boldsymbol{r}' N(\boldsymbol{r},\boldsymbol{r}')\chi(\boldsymbol{r}')$$

$$\to -\frac{\hbar^2}{2\mu}\nabla^2\chi^{(N)} + (V\chi^{(N)}) = E\chi^{(N)} \quad (\chi^{(N)} = \mathcal{N}^{1/2}\chi)$$

$$H(\boldsymbol{r},\boldsymbol{r}') = \langle \boldsymbol{r}B_1B_2\ldots|H|\mathcal{A}(\boldsymbol{r}'B_1B_2\ldots)\rangle$$

$$N(\boldsymbol{r},\boldsymbol{r}') = \langle \boldsymbol{r}B_1B_2\ldots|\mathcal{A}(\boldsymbol{r}'B_1B_2\ldots)\rangle$$

- **When (wave length of $\chi$) >> (baryon size),**

$$V(\boldsymbol{r}) \simeq \Delta K + \langle V\mathcal{A}\rangle/\langle\mathcal{A}\rangle$$

# Norm Kernel

- **Antisymmetrizer makes the calculation complicated !**

$$\mathcal{A} = [1 - 9(P_{36} + P_{39} + P_{69}) + 27(P_{369} + P_{396}) + 54(P_{25}\,P_{39} + P_{35}\,P_{69} + P_{38}\,P_{69})]\,\mathcal{A}_B - 216 P_{25}\,P_{38}\,P_{69}\ ,$$

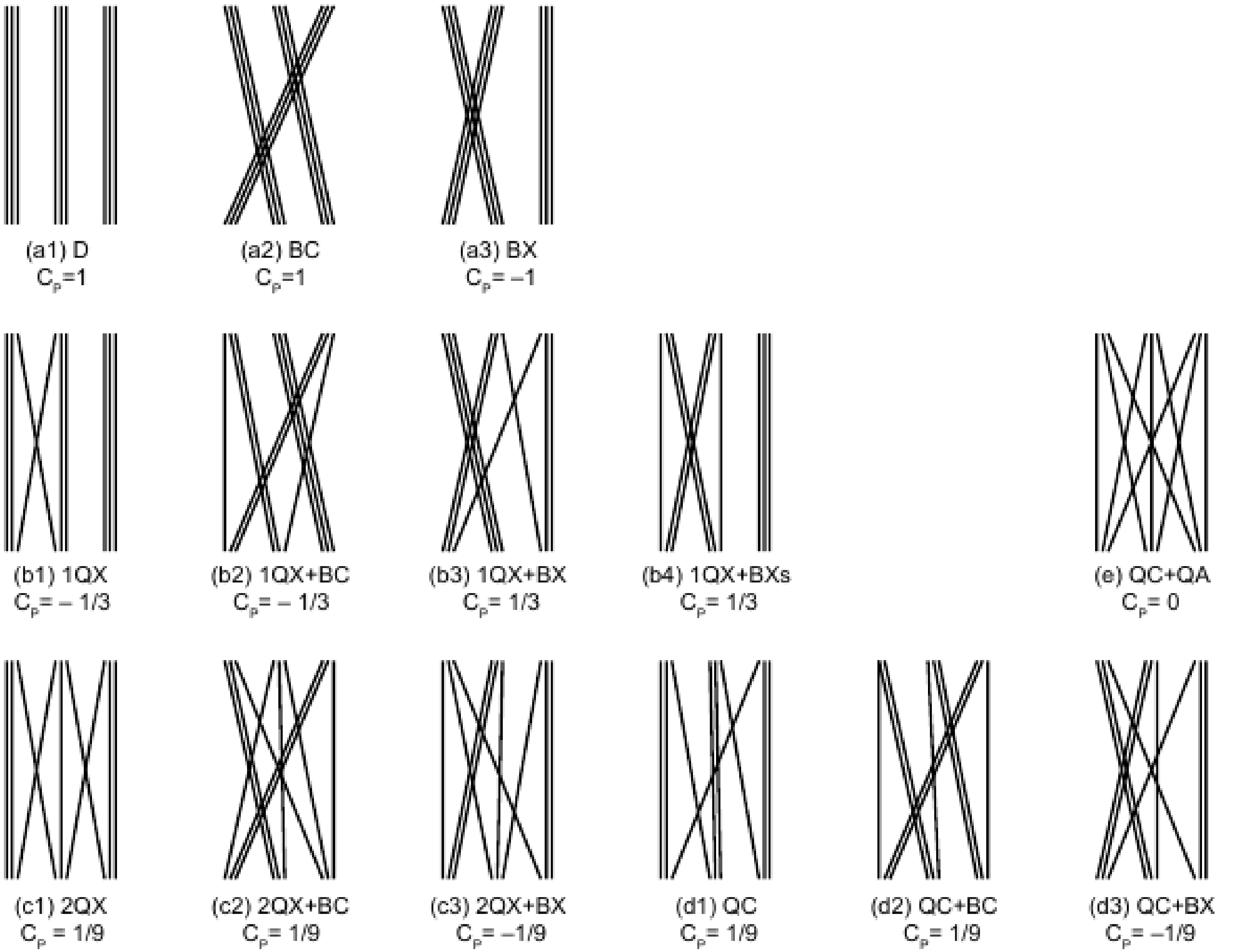
$$\mathcal{A}_B = \sum_{\mathcal{P}} (-1)^{\pi(\mathcal{P})}\,\mathcal{P}$$

*Toki, Suzuki, Hecht ('82)*

- **Recent work**

*Nakamoto, Suzuki ('16)*

**→ Norm kernel of 3 octet B**



# Norm Kernel

- **Single baryon w.f.** $|\psi_A\rangle = \mathcal{A}/\sqrt{3!} \times \varepsilon_{abc}/\sqrt{3!} \times [|\,\text{Flavor}\,\rangle \otimes |\,\text{Spin}\,\rangle \otimes |\,\text{Spatial w.f.}\rangle]^{abc}$.

| $B$ | $\vert\,\text{Flavor}\rangle$ | $\vert\,\text{Spin}\rangle$ |
|---|---|---|
| $n_\uparrow$ | $\vert\,ddu\,\rangle/\sqrt{2}$ | $\vert\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow\rangle/\sqrt{6}$ |
| $p_\uparrow$ | $\vert\,uud\,\rangle/\sqrt{2}$ | $\vert\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow\rangle/\sqrt{6}$ |
| $\Lambda_\uparrow$ | $\vert\,uds\,\rangle$ | $\vert\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow\rangle/\sqrt{2}$ |
| $\Sigma^-_\uparrow$ | $\vert\,dds\,\rangle/\sqrt{2}$ | $\vert\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow\rangle/\sqrt{6}$ |
| $\Sigma^0_\uparrow$ | $\vert\,uds\,\rangle$ | $\vert\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow\rangle/\sqrt{6}$ |
| $\Sigma^+_\uparrow$ | $\vert\,uus\,\rangle/\sqrt{2}$ | $\vert\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow\rangle/\sqrt{6}$ |
| $\Xi^-_\uparrow$ | $\vert\,ssd\,\rangle/\sqrt{2}$ | $\vert\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow\rangle/\sqrt{6}$ |
| $\Xi^0_\uparrow$ | $\vert\,ssu\,\rangle/\sqrt{2}$ | $\vert\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow\rangle/\sqrt{6}$ |

- **Two baryon w.f.**

$$|\psi_{\mathcal{A}}(n_\uparrow, n_\downarrow)\rangle = \frac{1}{\sqrt{6!}}\,|\,\mathcal{A}[\psi(n_\uparrow)\psi(n_\downarrow)]\rangle$$

**Norm**

$$\begin{aligned}
\mathcal{N}_{\mathcal{A}} =& \langle\psi_{\mathcal{A}}(n_\uparrow, n_\downarrow)\,|\,\psi_{\mathcal{A}}(n_\uparrow, n_\downarrow)\rangle \\
=& \langle\psi(n_\uparrow)\psi(n_\downarrow)\,|\,\mathcal{A}[\psi(n_\uparrow)\psi(n_\downarrow)]\rangle \\
=& \frac{1}{(3!)^2}\sum_{i,j,k,l} c_i^*(n_\uparrow)c_j^*(n_\downarrow)c_k(n_\uparrow)c_l(n_\downarrow)\,\varepsilon_{abc}\,\varepsilon_{def}\,\varepsilon_{a'b'c'}\,\varepsilon_{d'e'f'} \\
& \times \langle\phi_i^{abc}(n_\uparrow)\phi_j^{def}(n_\downarrow)\,|\,\mathcal{A}\,[\phi_k^{a'b'c'}(n_\uparrow)\phi_l^{d'e'f'}(n_\downarrow)]\rangle \\
=& \sum_{i,j,k,l} c_i^*(n_\uparrow)c_j^*(n_\downarrow)c_k(n_\uparrow)c_l(n_\downarrow)\sum_P C_P(\phi_i\phi_j, \phi_k\phi_l)\,F_P(\phi_i\phi_j, \phi_k\phi_l)
\end{aligned}$$

**Anti-symmetrization**

$$\mathcal{A}[1^a1^b1^c2^d2^e2^f] = 1^a1^b1^c2^d2^e2^f - 1^a1^b2^d1^c2^e2^f + 1^a2^e2^d1^c1^b2^f + \cdots$$

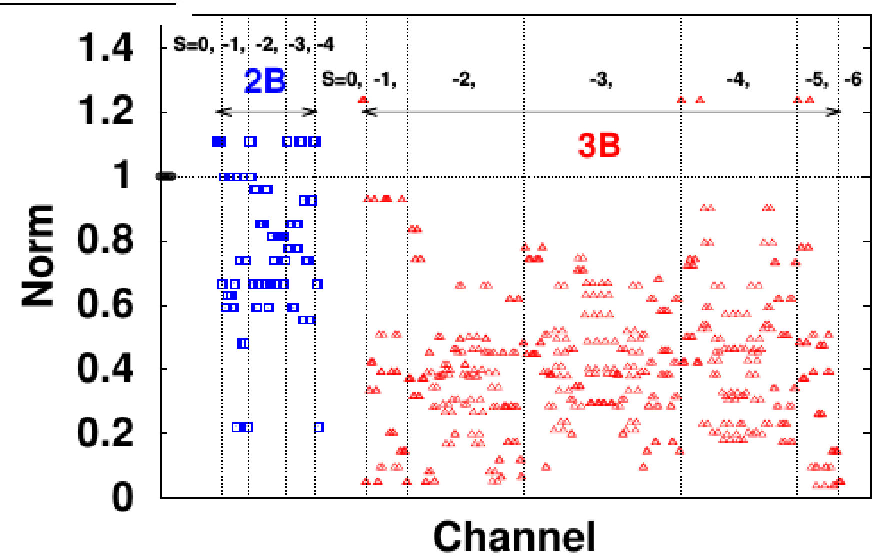
$$C_P = -\frac{1}{(3!)^2}\varepsilon_{abd}\varepsilon_{cef}\varepsilon_{abc}\varepsilon_{def} = -\frac{1}{36}\,2\delta_{dc}\,2\delta_{cd} = -\frac{1}{3}$$

$$F_P(\phi_i\phi_j, \phi_k\phi_l) = \langle\phi_i(n_\uparrow)\phi_j(n_\downarrow)\,|\,P[\phi_k(n_\uparrow)\phi_l(n_\downarrow)]\rangle_{\text{fss}} = 0 \text{ or } 1$$ ← **Numerical**

# *Norm Kernel*

| Baryon(s) | $\mathcal{N}_\mathcal{A}$ | $\mathcal{T}_\mathcal{A}$ | $\mathcal{T}$ | $\mathcal{T}_{nB}(n=2,3)$ |
|---|---|---|---|---|
| $(NN)_{(S,T)=(0,1),(1,0)}$ | 10/9 | 0 | 0 | 0 |
| $N_\uparrow\Lambda_\uparrow, N_\downarrow\Lambda_\downarrow$ | 1 | 20/3 | 20/3 | 20/3 |
| $N_\uparrow\Lambda_\downarrow, N_\downarrow\Lambda_\uparrow$ | 1 | 10/3 | 10/3 | 10/3 |
| $(\Lambda\Lambda)_{S=0}$ | 1 | 18/3 | 18/3 | 18/3 |
| $(NNN)_{(S,T)=(1/2,1/2)}$ | 100/81 | 0 | 0 | 0 |
| $n_\uparrow n_\downarrow\Lambda, p_\uparrow p_\downarrow\Lambda$ | 25/27 | 350/27 | 14 | 12/3 |
| $n_\uparrow p_\uparrow\Lambda_\uparrow, n_\downarrow p_\downarrow\Lambda_\downarrow$ | 25/27 | 750/27 | 30 | 50/3 |
| $n_\uparrow p_\uparrow\Lambda_\downarrow, n_\downarrow p_\downarrow\Lambda_\uparrow$ | 25/27 | 250/27 | 10 | 10/3 |
| $n_\uparrow p_\downarrow\Lambda, n_\downarrow p_\uparrow\Lambda$ | 25/27 | 425/27 | 17 | 21/3 |
| $N\Lambda_\uparrow\Lambda_\downarrow$ | 45/54 | 1035/54 | 23 | 21/3 |

**Not very small**




*AO, Kashiwa, Morita ('16)*

# KMT matrix element

- **Reduction of KMT interaction to 3 quark pot.**

$$V_{\rm KMT} \simeq -2g_{\rm D}\int d^3x\, \varepsilon_{ijk}\, u^\dagger(\boldsymbol{x})q_i(\boldsymbol{x})\, d^\dagger(\boldsymbol{x})q_j(\boldsymbol{x})\, s^\dagger(\boldsymbol{x})q_k(\boldsymbol{x})$$

$$= -2g_{\rm D}\boxed{\varepsilon_{ijk}\sum_{\{\alpha,\beta,\gamma\}} \hat{T}^{u,i}_\alpha \hat{T}^{d,j}_\beta \hat{T}^{s,k}_\gamma}\delta(\boldsymbol{x}_\alpha-\boldsymbol{x}_\beta)\delta(\boldsymbol{x}_\beta-\boldsymbol{x}_\gamma)$$

- **Flavor exchanging operator**

$$\hat{\mathcal{T}}^{\rm KMT} = \sum_{\{\alpha,\beta,\gamma\}} \varepsilon_{ijk}\, \hat{T}^{u,i}_\alpha \hat{T}^{d,j}_\beta \hat{T}^{s,k}_\gamma$$

$$\mathcal{T}_A \equiv \langle \psi_A \mid \hat{\mathcal{T}}^{\rm KMT} \mid \psi_A \rangle \qquad \mathcal{T} = \mathcal{T}_A/\mathcal{N}_A$$

- **Subtract the two-body part**

$$\mathcal{T}_{3B}(n_\uparrow n_\downarrow \Lambda_\uparrow) = \mathcal{T}(n_\uparrow n_\downarrow \Lambda_\uparrow) - \mathcal{T}(n_\uparrow \Lambda_\uparrow) - \mathcal{T}(n_\downarrow \Lambda_\uparrow)$$

# KMT matrix element

$$\langle \phi \mid V_{\rm KMT} \mid \phi' \rangle = \sum_{\{\alpha,\beta,\gamma\}} \langle q_\alpha q_\beta q_\gamma \mid V_{\rm KMT} \mid q'_\alpha q'_\beta q'_\gamma \rangle \prod_{i \neq \{\alpha,\beta,\gamma\}} \langle q_i \mid q'_i \rangle$$

$$= -2g_{\rm D} \langle \sigma \mid \sigma' \rangle \sum_{\{\alpha,\beta,\gamma\}} F^{\rm KMT}_{\alpha\beta\gamma}(f,f') R^{\rm KMT}_{\alpha\beta\gamma}(\varphi,\varphi') ,$$

product w.f.

**irrelevant quarks**

$$\langle \sigma \mid \sigma' \rangle = \prod_\alpha \langle \sigma_\alpha \mid \sigma'_\alpha \rangle ,$$

**flavor matching (numerical)**

$$F^{\rm KMT}_{\alpha\beta\gamma}(f,f') = \langle f \mid \varepsilon_{ijk} \hat{T}^{u,i}_\alpha \hat{T}^{d,j}_\beta \hat{T}^{s,k}_\gamma \mid f' \rangle$$

$$= \delta_{u,f_\alpha} \delta_{d,f_\beta} \delta_{s,f_\gamma} \sum_{ijk} \varepsilon_{ijk} \boxed{\delta_{i,f'_\alpha} \delta_{j,f'_\beta} \delta_{k,f'_\gamma}} \prod_{\mu \neq \{\alpha,\beta,\gamma\}} \delta_{f_\mu, f'_\mu} ,$$

$$R^{\rm KMT}_{\alpha\beta\gamma}(\varphi,\varphi') = \langle \varphi \mid \delta(x_\alpha - x_\beta)\delta(x_\beta - x_\gamma) \mid \varphi' \rangle$$

$$= \int d^3x \varphi^*_\alpha(x) \varphi^*_\beta(x) \varphi^*_\gamma(x) \varphi'_\alpha(x) \varphi'_\beta(x) \varphi'_\gamma(x) \prod_{\mu \neq \alpha,\beta,\gamma} \langle \varphi_\mu \mid \varphi'_\mu \rangle .$$

# *KMT matrix element*

| Baryon(s) | $\mathcal{N}_{\mathcal{A}}$ | $\mathcal{T}_{\mathcal{A}}$ | $\mathcal{T}$ | $\mathcal{T}_{nB}(n=2,3)$ |
|---|---|---|---|---|
| $(NN)_{(S,T)=(0,1),(1,0)}$ | 10/9 | 0 | 0 | 0 |
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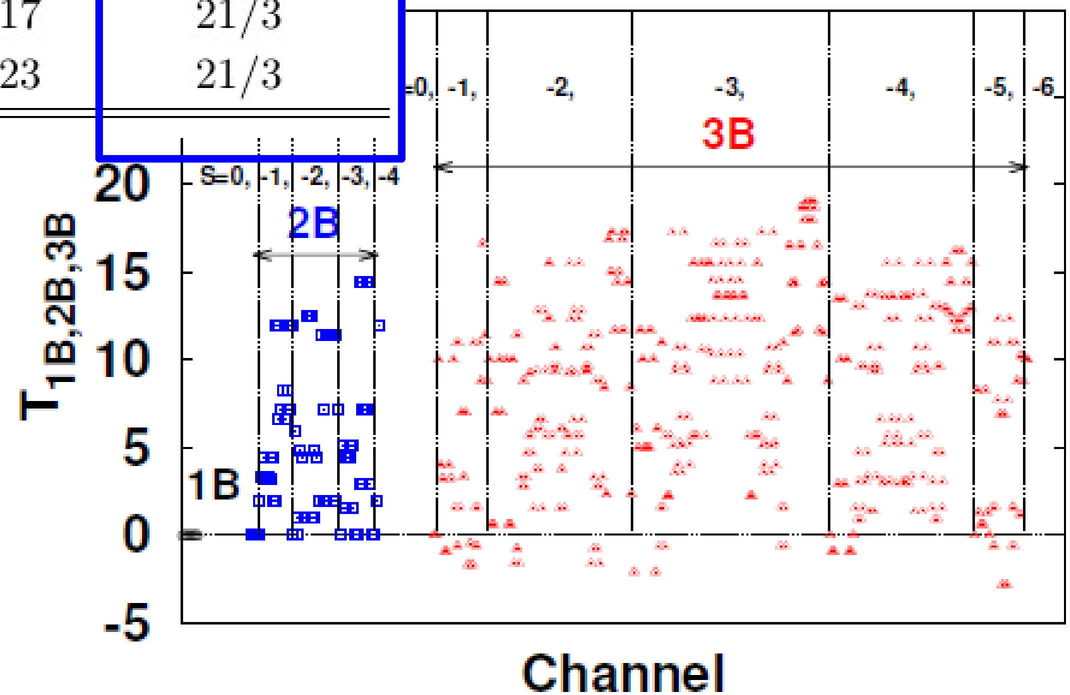
| $N\Lambda_\uparrow\Lambda_\downarrow$ | 45/54 | 1035/54 | 23 | 21/3 |

**Big for np$\Lambda$ (S=3/2)**




**KMT matrix elements strongly depend on the channel**

# 3B potential from KMT interaction

- **3q int. → 3B potential**

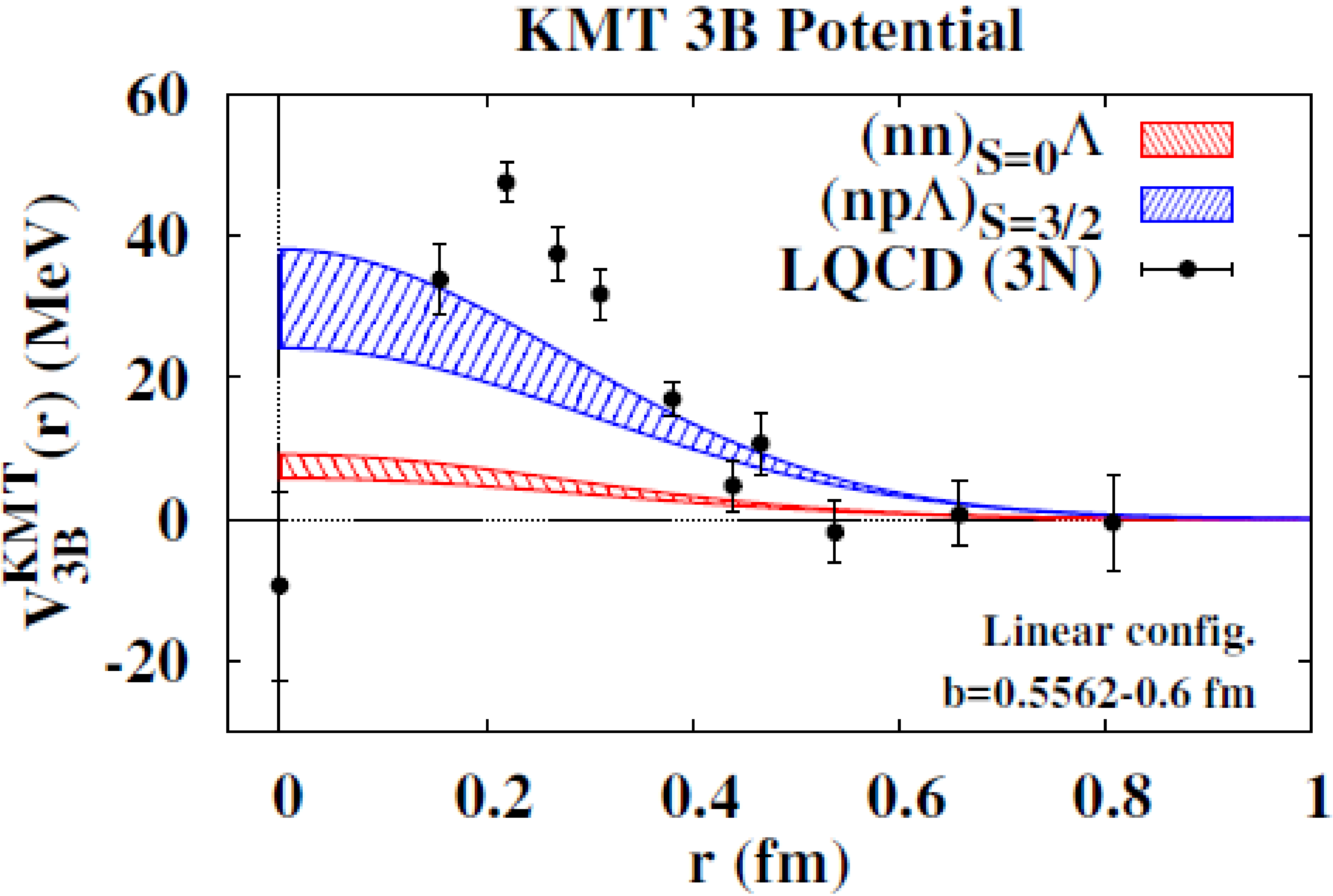
$$V_{3B}^{KMT} = -2 g_D T_{3B} \int d^3x \varphi^*_{R_a}(x)\varphi^*_{R_b}(x)\varphi^*_{R_c}(x)\varphi_{R_d}(x)\varphi_{R_e}(x)\varphi_{R_f}(x)$$

$$V_{3B}^{\mathrm{KMT}}(\boldsymbol{R}_1, \boldsymbol{R}_2, \boldsymbol{R}_3) \simeq V_0 T_{3B} \exp\left[-\frac{2\nu}{3}(\boldsymbol{R}_{12}^2 + \boldsymbol{R}_{23}^2 + \boldsymbol{R}_{31}^2)\right]$$

$$V_0 \equiv \frac{-2g_{\mathrm{D}}}{(\sqrt{3}\pi b^2)^3} = \frac{-2g_{\mathrm{D}}\Lambda^5}{(\sqrt{3}\pi b^2\Lambda^2)^3}\Lambda = \begin{cases} 1.45\ \mathrm{MeV} & (b = 0.6\ \mathrm{fm})\ , \\ 2.29\ \mathrm{MeV} & (b = 0.5562\ \mathrm{fm})\ . \end{cases}$$

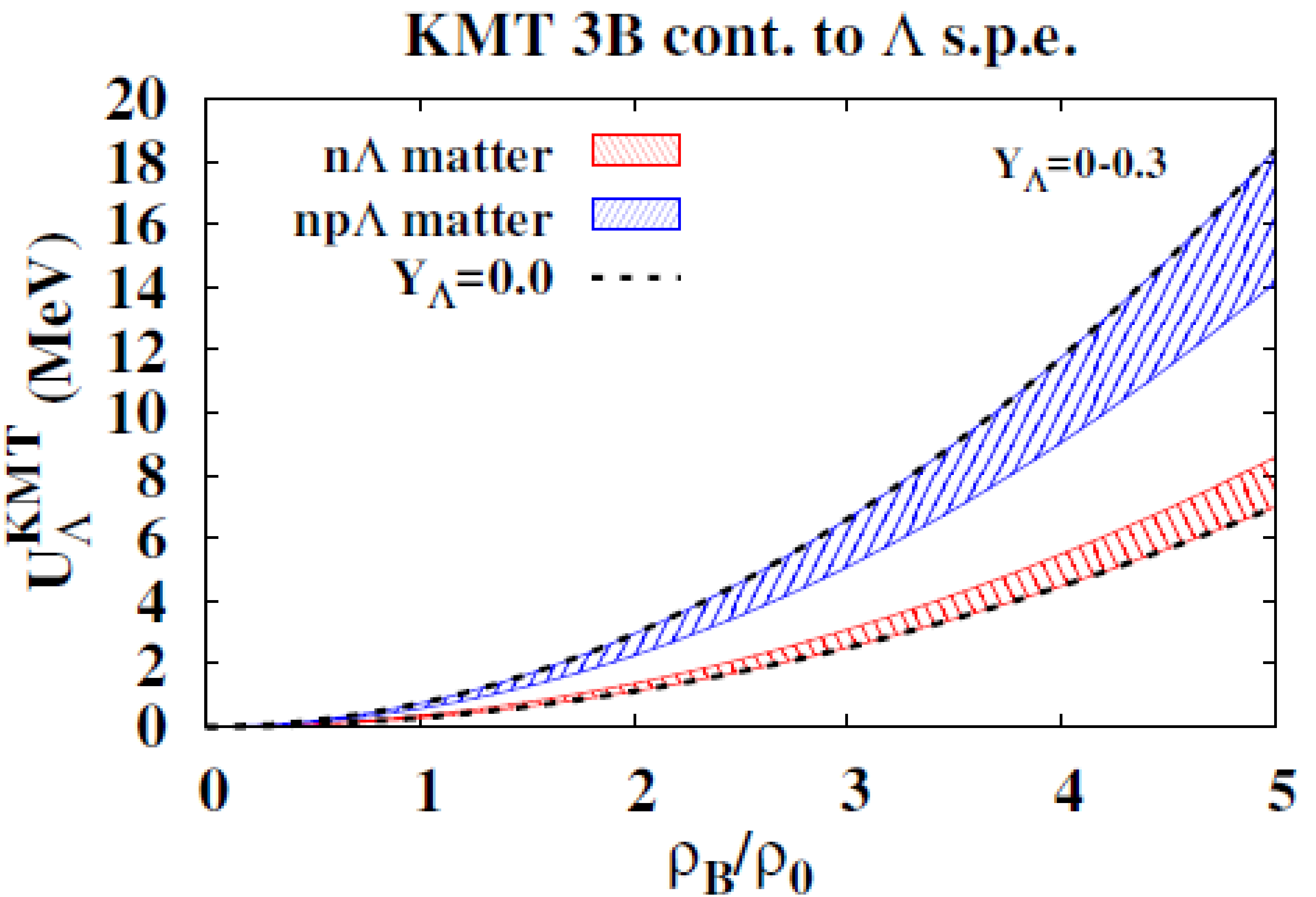
**Parameters are taken from**
***Hatsuda, Kunihiro ('94), Rehberg, Klevanski, Hufner ('96), Fujiwara, Suzuki, Nakamoto ('07), Oka, Yazaki ('81)***

# 3B potential from KMT interaction



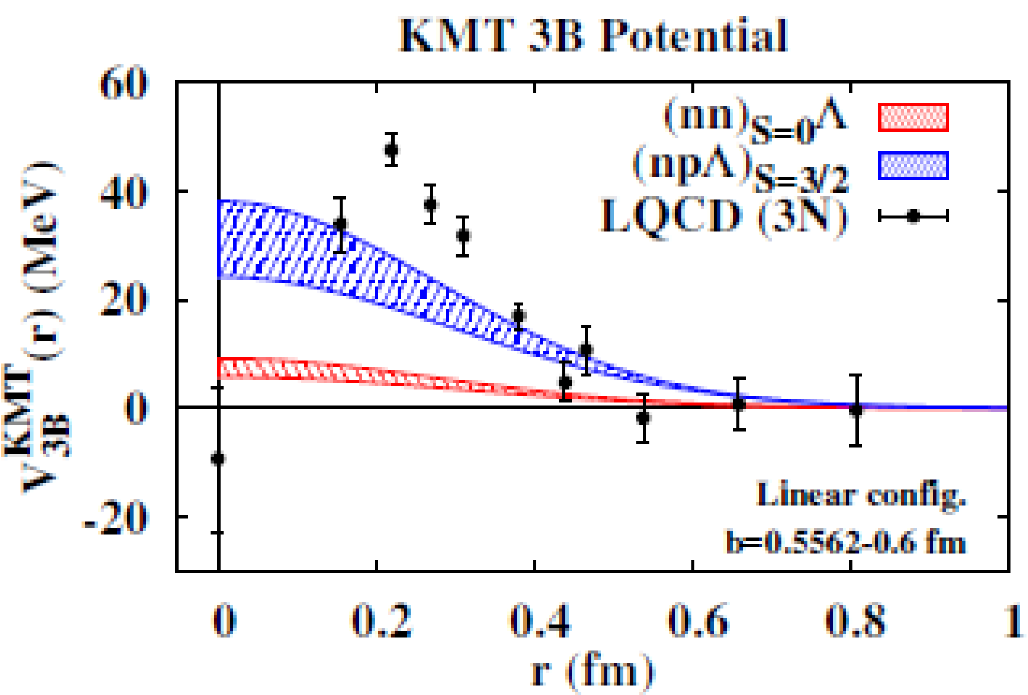

*Lattice data: Doi et al. (HAL QCD) ('07)*

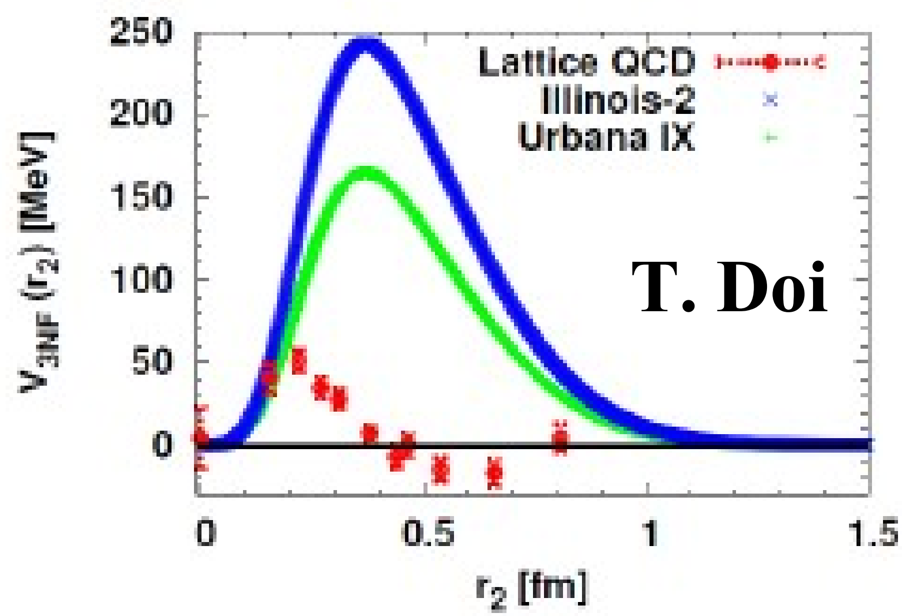
# KMT-3B Contribution to Λ potential




Density is assumed to be uniform. No correlation effects.

# 3B potential from KMT: Repulsive enough ?



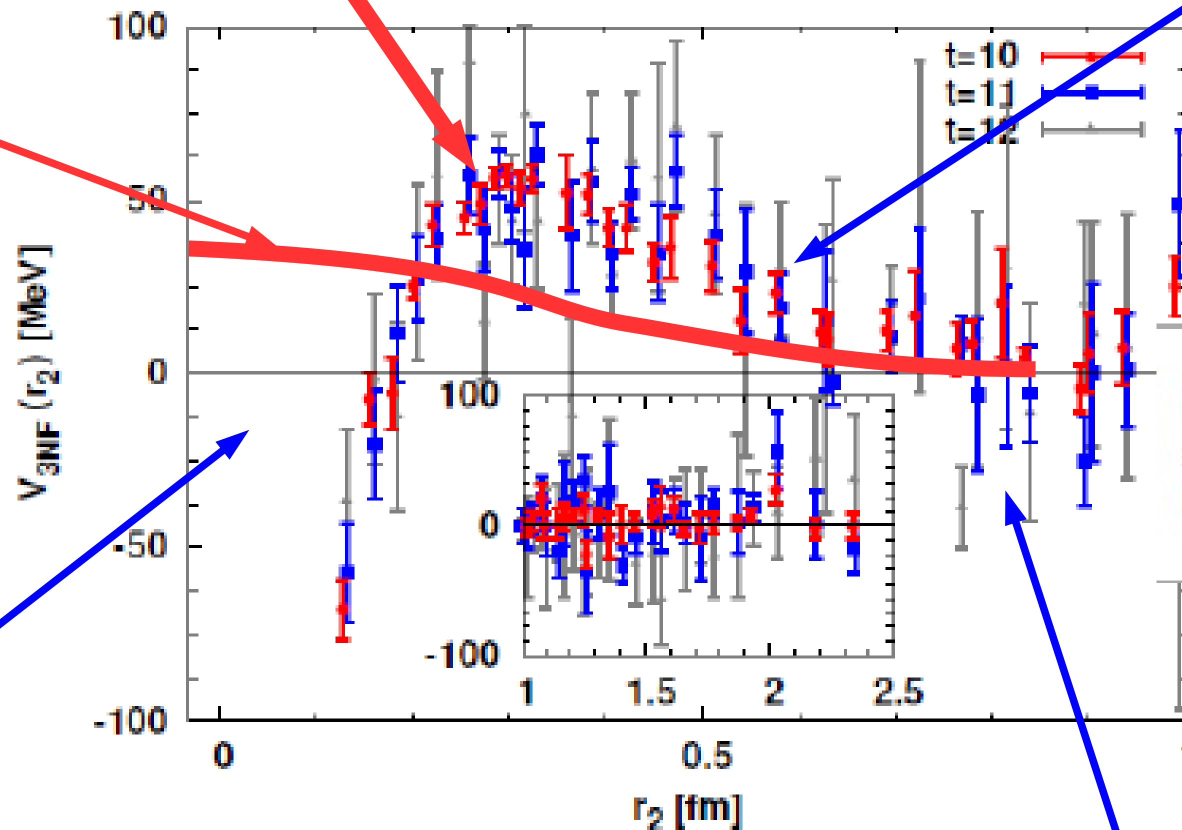
# Summary

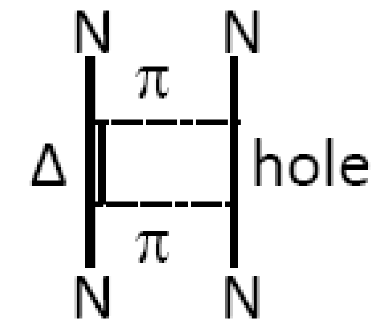
- Quark model three-baryon (3B) potential may be a promising method to evaluate the 3B potential at short distances.
- Kobayashi-Maskawa-'t Hooft (KMT) interaction generates 3q potential among u,d,s quarks, and generates 3B potential only when hyperons are involved.
- Expectation value of the KMT interaction is evaluated in the cases where 3B are located at the same spatial point.
  Matrix elements strongly depend on the baryon trio.
- 3B potential from KMT interaction is obtained.
  - It is comparable in strength to the lattice 3N potential.
  - More repulsive in np$\Lambda$ than in nn$\Lambda$
    (Negative contribution to symmetry energy.)
- 3B pot. from KMT is not strong enough to solve the hyperon puzzle, but contributes to hyperon suppression.

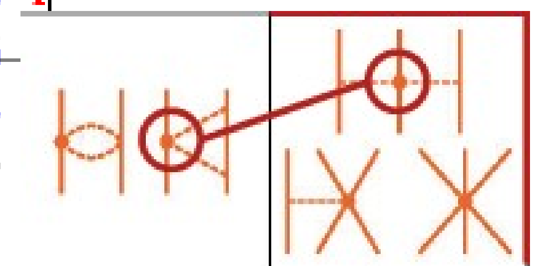
# *Three-Baryon force*

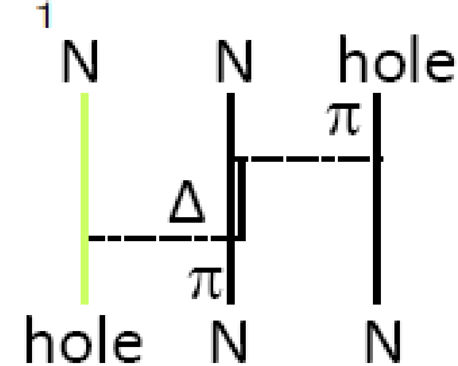
**What makes 3B repulsion at r ~ 0.5 fm ?**

**KMT**
**(ΛNN)**



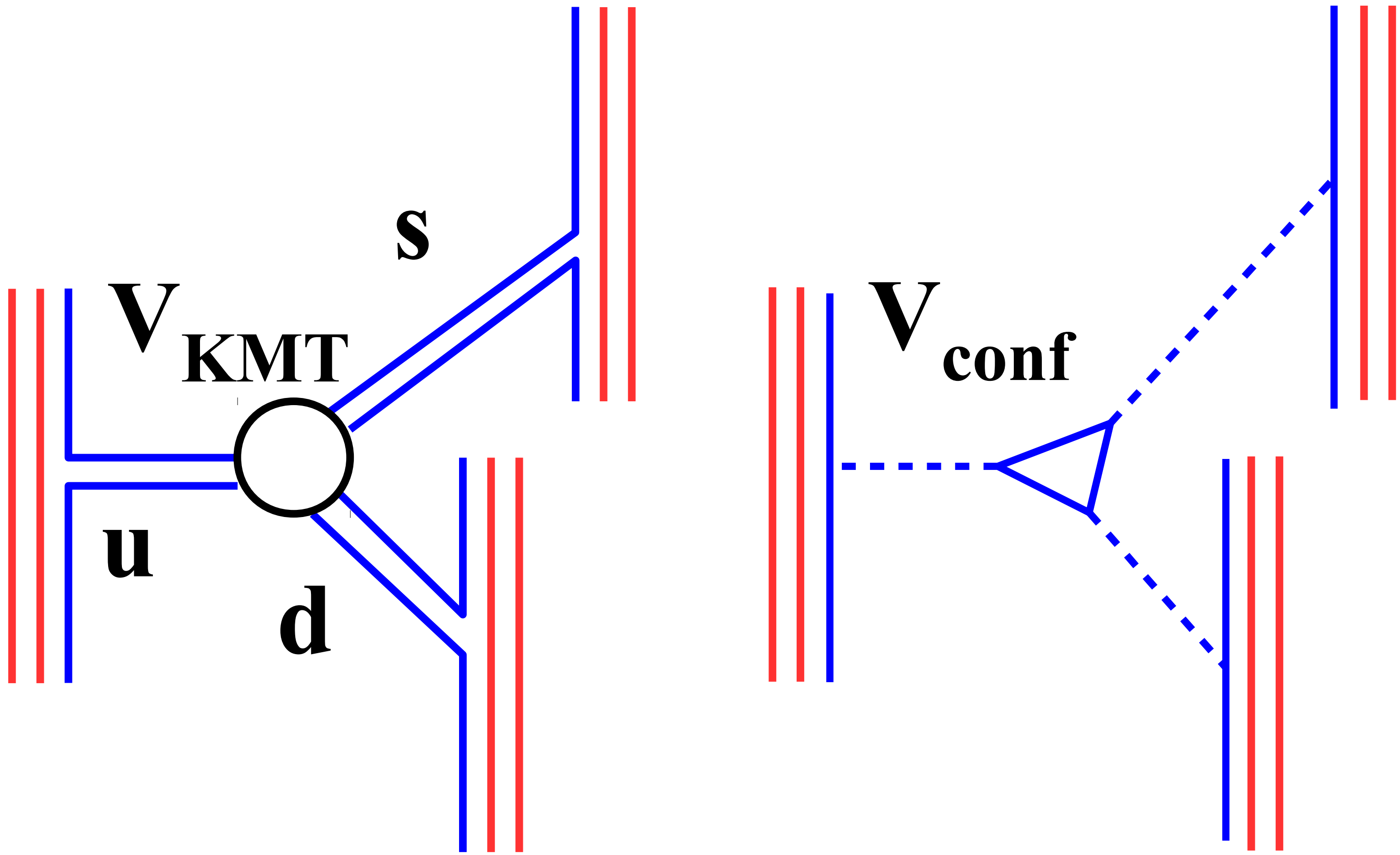






**pQCD**

**Taken from NPCSM 2016 talks,**
**Doi (Wed), Kohno (Thu), Tews (Thu)**

# Confinement Potential → 3B Potential ?




$$V_{\rm conf} = \sum_{\{\alpha,\beta,\gamma\}} \varepsilon_{abc}\varepsilon_{a'b'c'} f(\boldsymbol{x}_\alpha, \boldsymbol{x}_\beta, \boldsymbol{x}_\gamma)$$

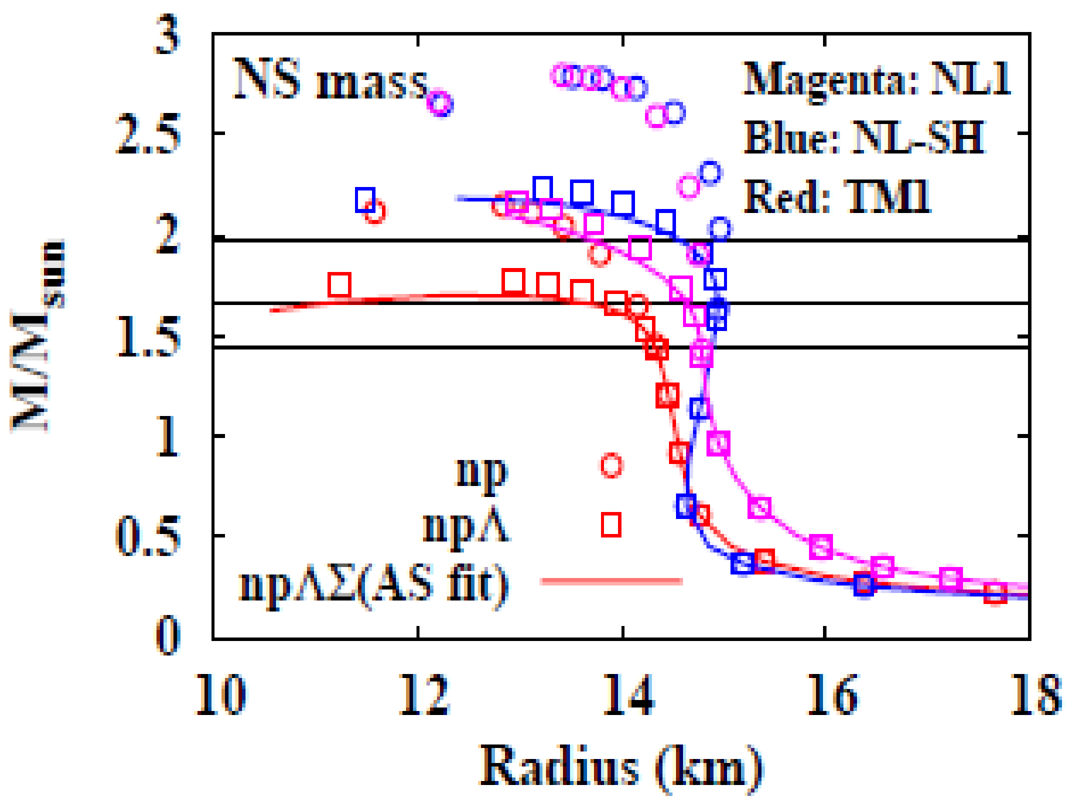
*Takahashi, Suganuma, Nemoto, Matsufuru ('02)*

***Thank you for your attention !***

# *Massive Neutron Stars with Hyperons*

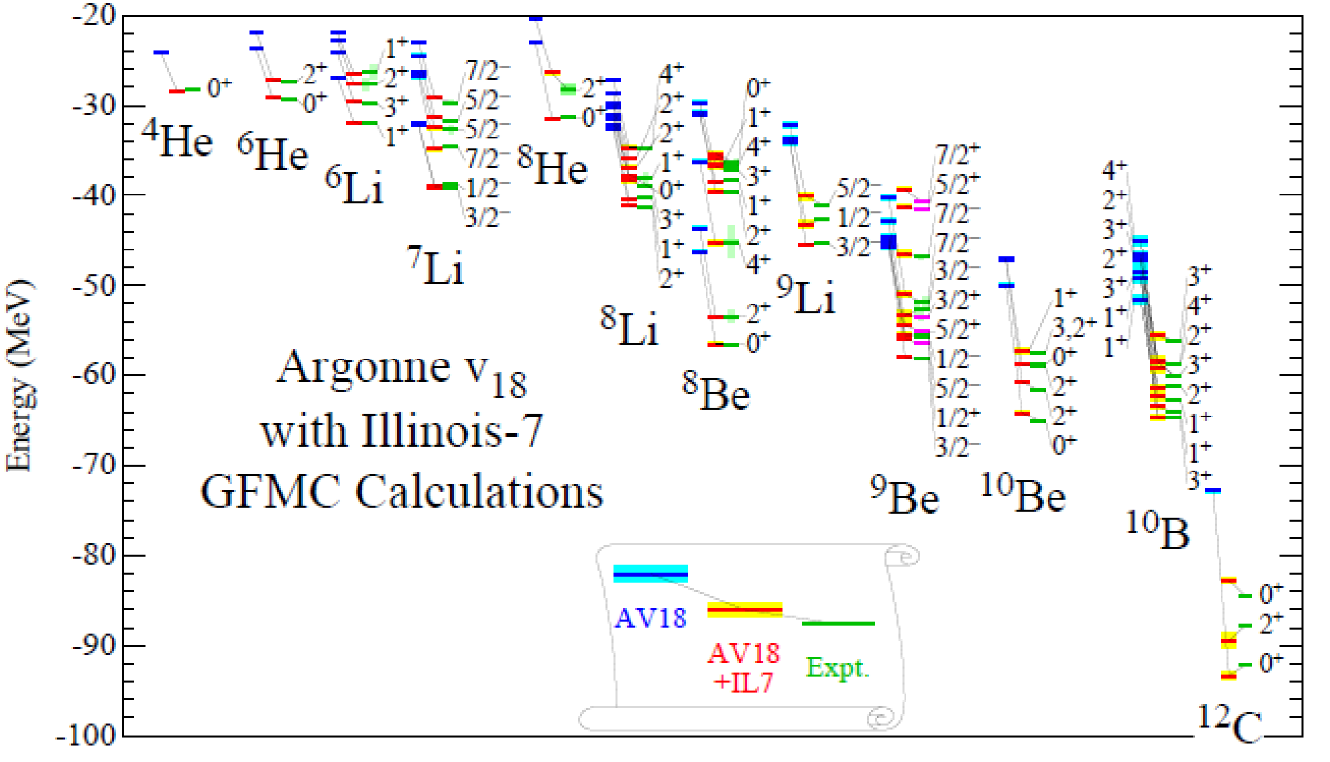
*Tsubakihara, Harada, AO, arXiv:1402.0979*

- **Ruled-out EOS with hyperons = GM3**
  **Glendenning & Moszkowski (1991)**
- **We did NOTHING special and find 2 $M_\odot$ NS can be supported.**
  - **"Typical" RMF for nucl. matter**
    **NL1, NL-SH, TM1**
    *Reinhardt et al. ('86); Sharma, Nagarajan, Ring ('93); Sugahara, Toki ('94).*
  - **$s\bar{s}$ mesons are introduced**
  - **Hypernuclear data**
    **Λ, ΛΛ hypernuclei**
    **Σ atomic shifts**
    **SU(3) relation to isoscalar -vector couplings**



# *What is necessary to solve the massive NS puzzle ?*

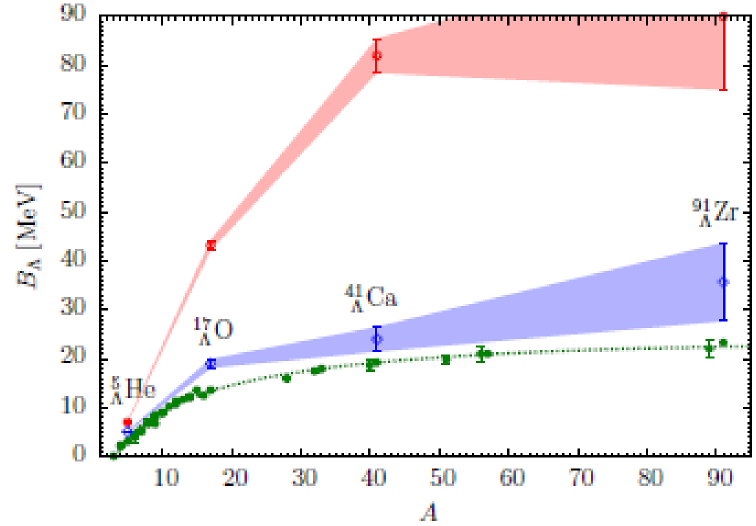
- **There are many "model" solutions.**
- **Ab initio calculation including three-baryon force (3BF)**
  - **Bare 2NF+Phen. 3NF(UIX, IL2-7) + many-body theory (verified in light nuclei).**
  - **Chiral EFT (2NF+3NF) + many-body theory**
  - **Dirac-Bruckner-HF (no 3NF)**




*J. Carlson et al. ('14)*

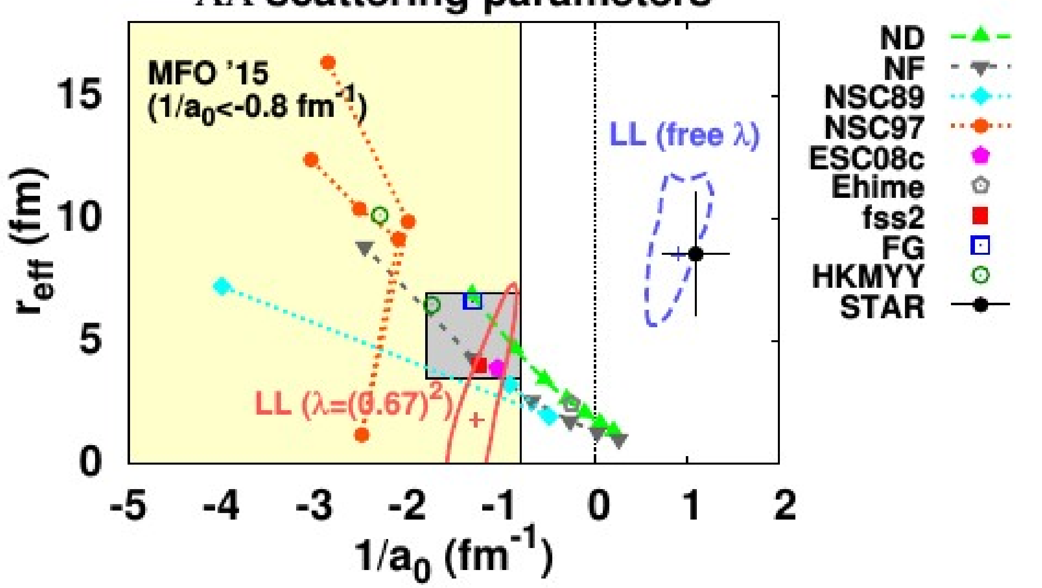
# 3BF including Hyperons

- **3BF incl. YNN, YYN and YYY should exist and contribute to EOS.**
  *Nishizaki, Takatsuka, Yamamoto ('02)*
  - **Chiral EFT, Multi-Pomeron exch., Quark Pauli, Lattice 3BF, SJ, ..**
    Kohno('10); Heidenbauer+('13); Yamamoto+('14); Nakamoto, Suzuki; Doi+(HALQCD,'12); Tamagaki('08); …
  - **Quant. MC study** *Lonardoni et al.('14)*
  - **Quark Meson Coupling**
    *Miyatsu et al.; Thomas (HHIQCD)*
  - **ΛΛN** *K. Morita, T. Furumoto, AO, PRC91('15)024916*

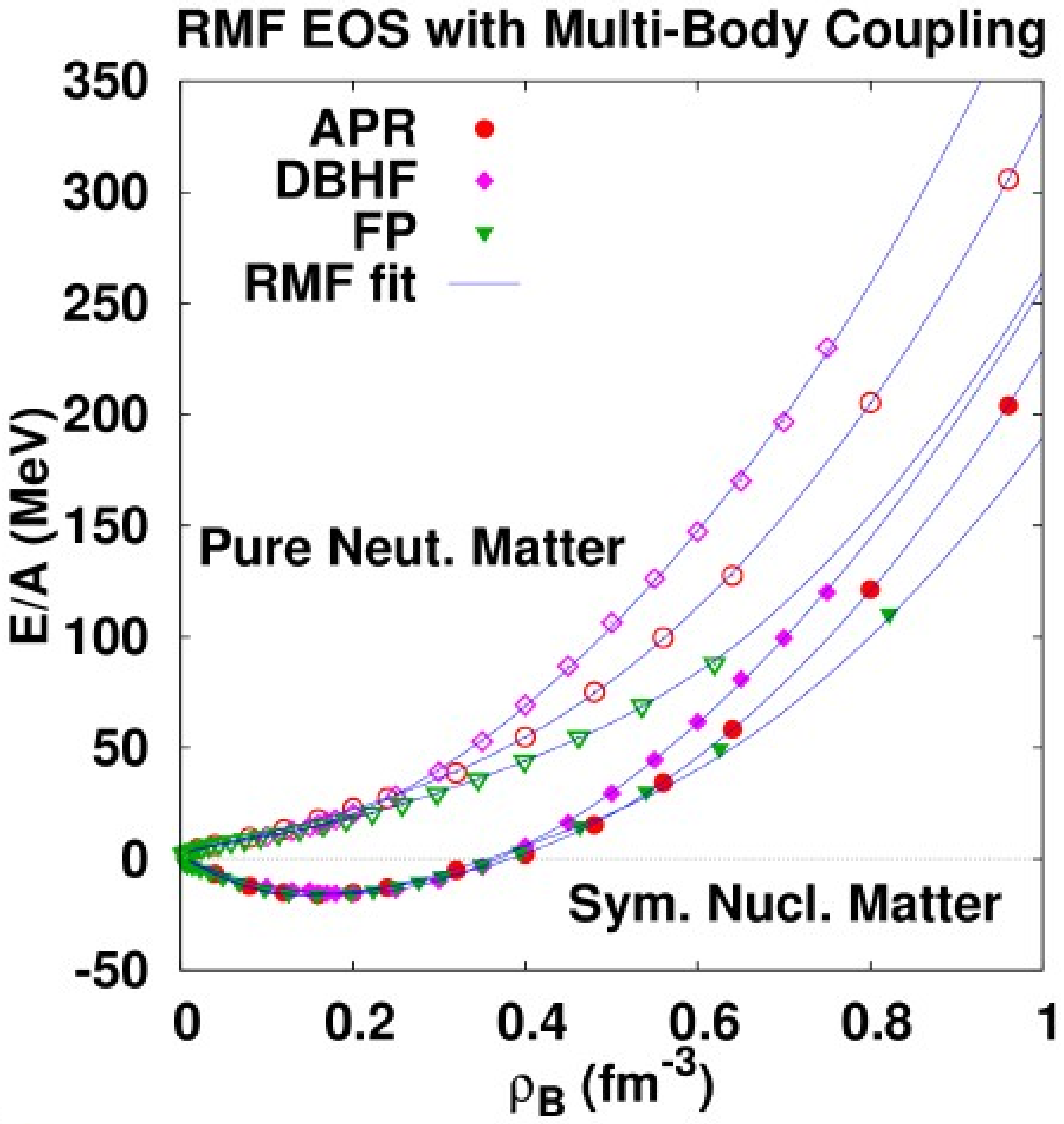



**Caveat: Missing data**

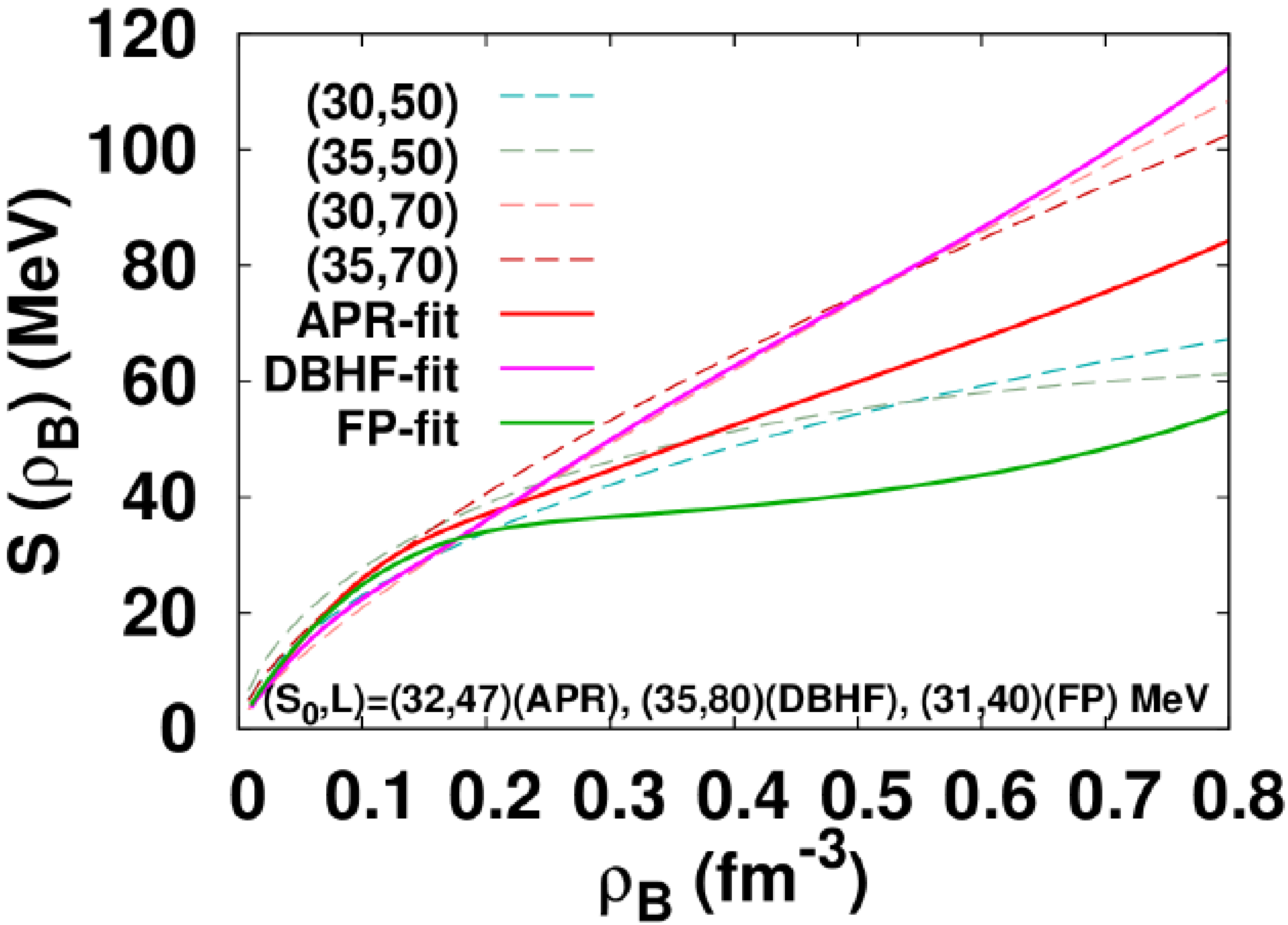
ΛΛ scattering parameters



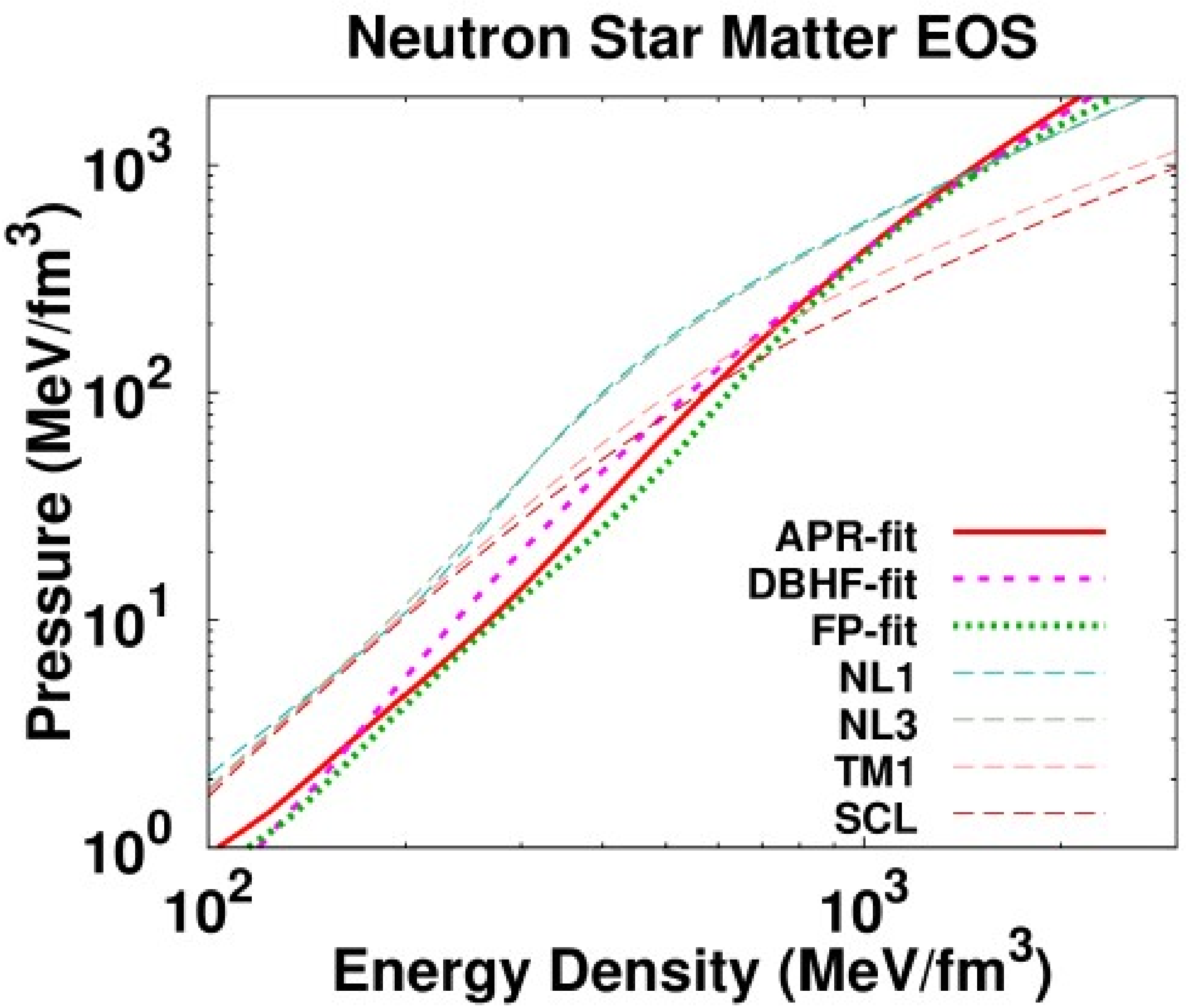
# *Fitting "Ab initio" EOS via RMF*

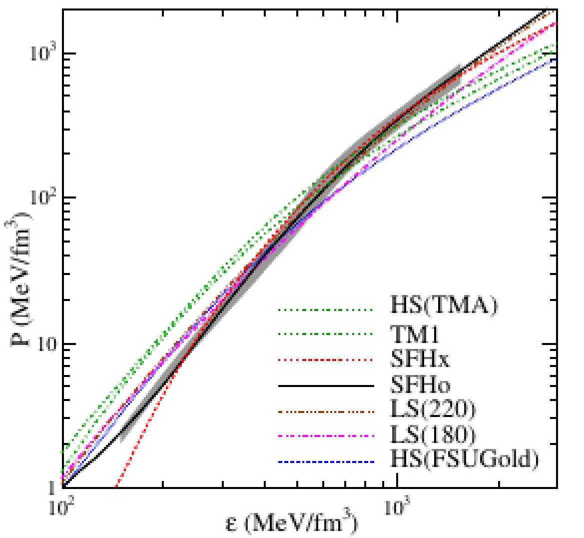


# *Symmetry Energy*



# Neutron Star Matter EOS

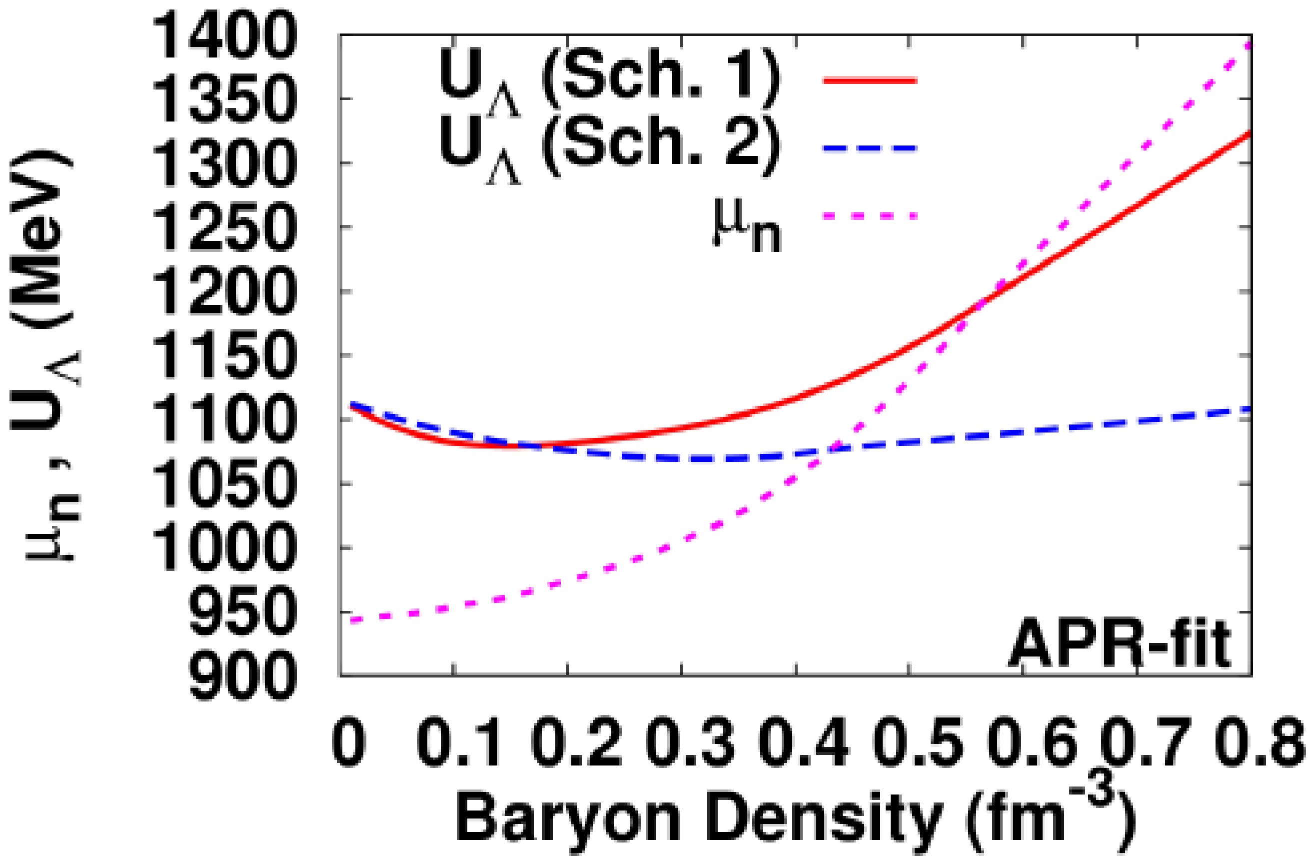



*A. W. Steiner, M. Hempel, T. Fischer, ApJ 774 (2013) 17 (TMA+NSE w/ excl. vol.)*

# *NS matter in "ab initio"-fit + Λ*

- **Λ potential in nuclear matter at $\rho_0$ ~ -30 MeV**
  - **Scheme 1: $U_\Lambda(\rho) = \alpha\, U_N(\rho)$**
  - **Scheme 2: $U_\Lambda(\rho) = 2/3\, U^{n=2}_N(\rho) + \beta\, U^{n>2}_N(\rho)$**



# M-R curve of Neutron Stars