Three Baryon Interaction in the Quark Cluster Model

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

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YITP, Kyoto U.

QH seminar, Nov. 11, 2016

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

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  - Hyperon Puzzle
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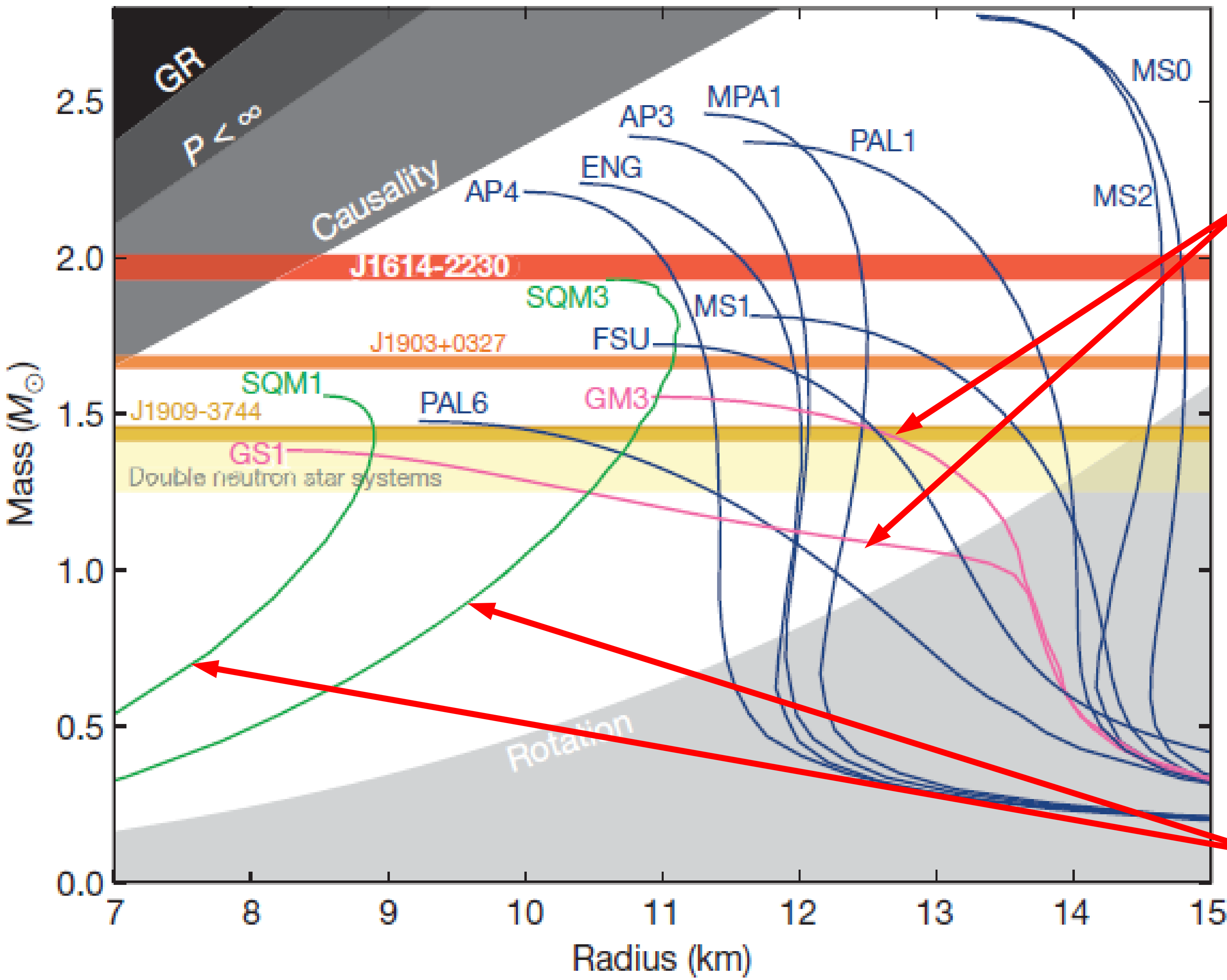
Hyperon Puzzle (or Hyperon Crisis)

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



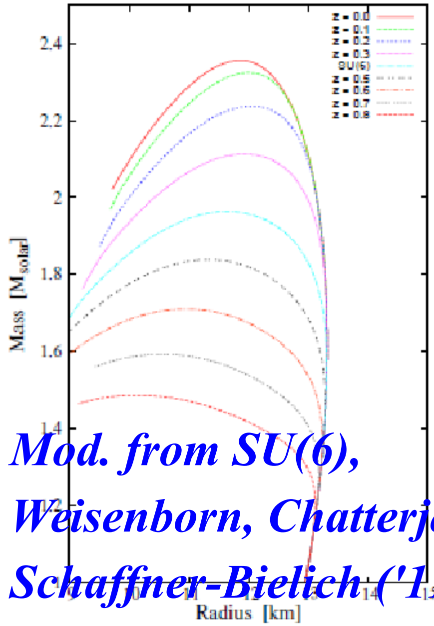
EOS with hyperons or Kaons

Quark matter EOS

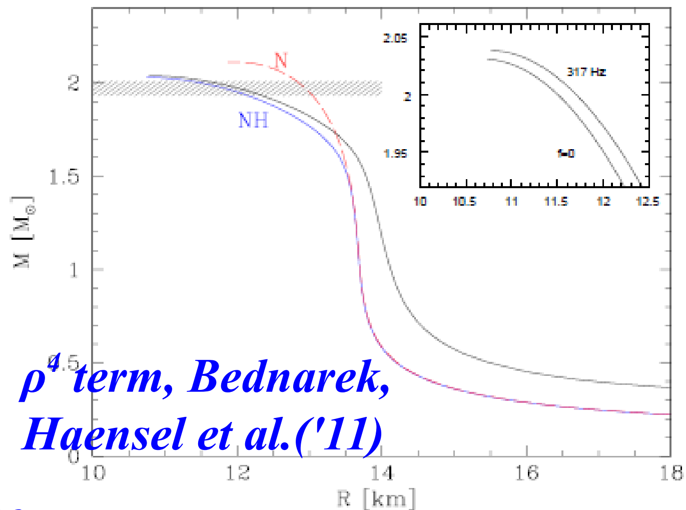
Proposed Solutions

- **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 ?**

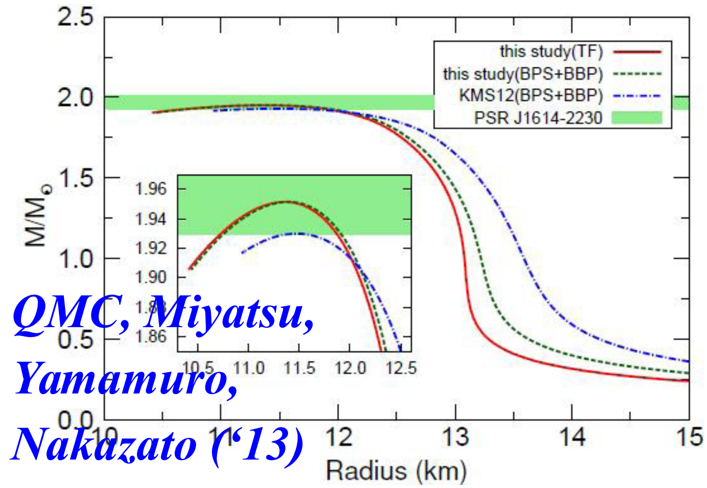
Massive Neutron Stars with Hyperons



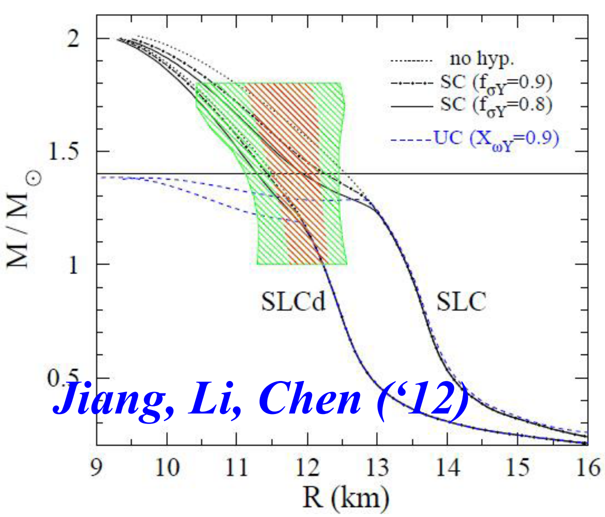
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



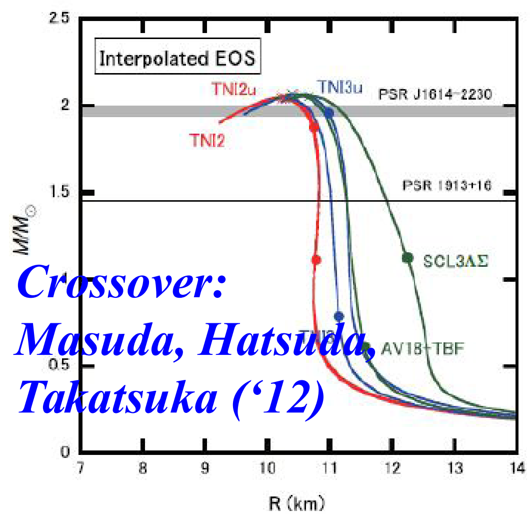
ρ^4 term, Bednarek, Haensel et al.('11)



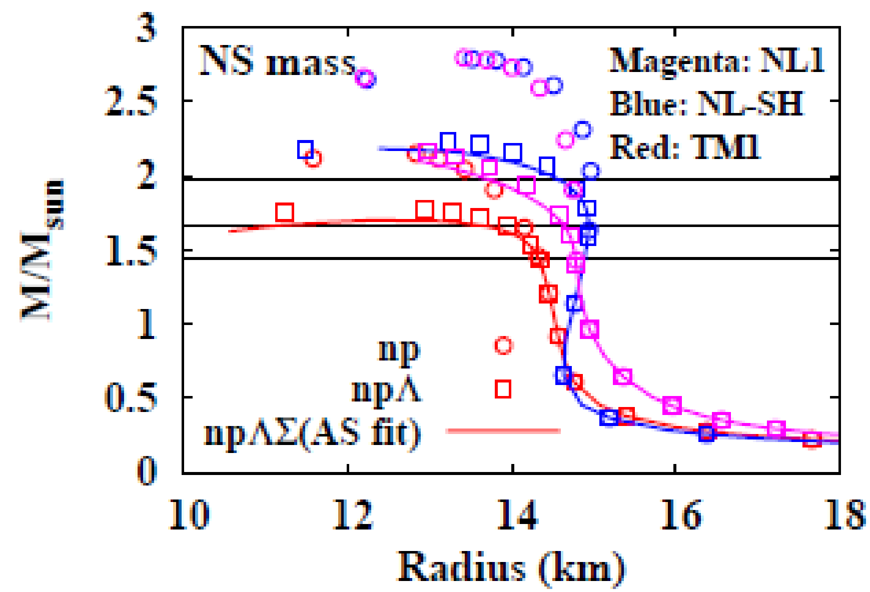
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



Crossover: Masuda, Hatsuda, Takatsuka ('12)

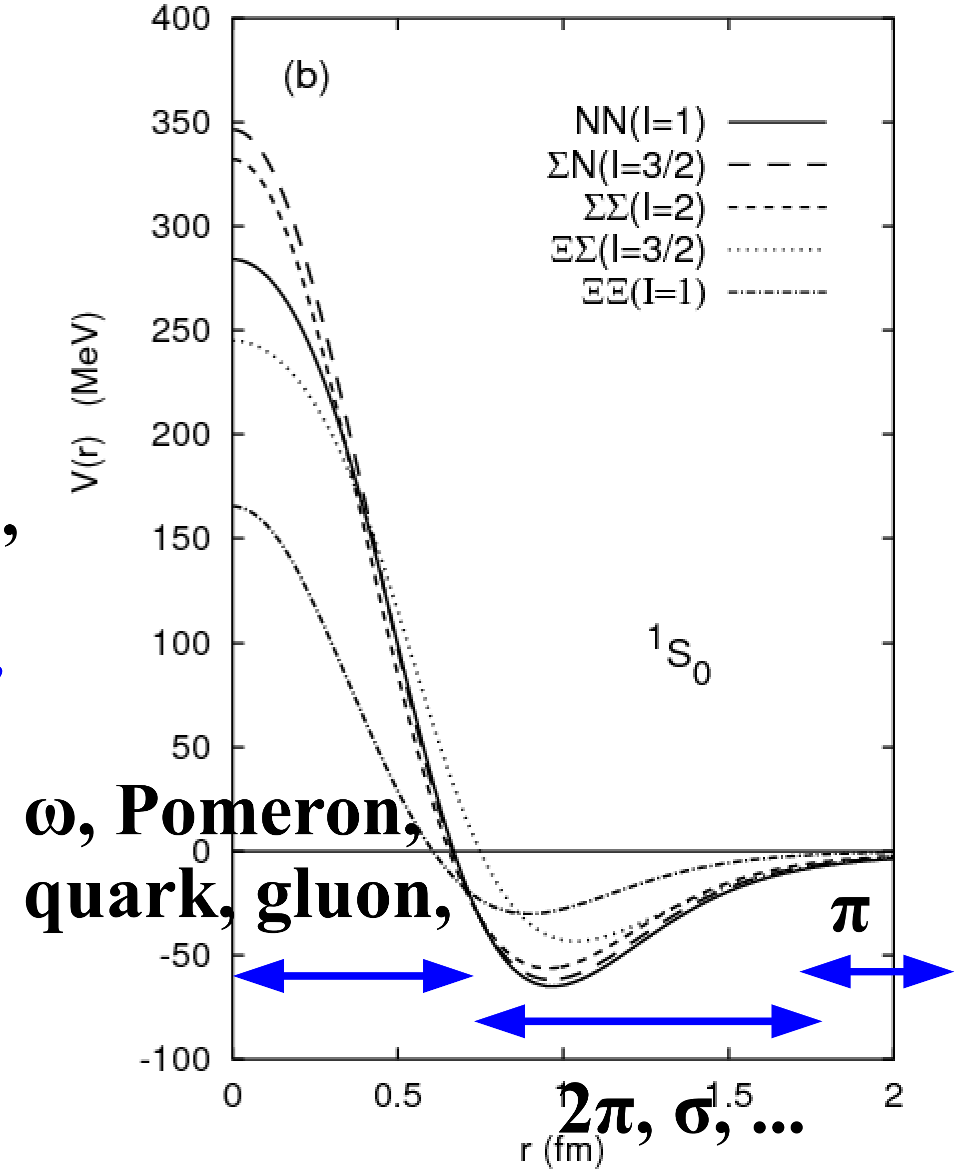


Tsubakihara, Harada, AO, arXiv:1402.0979

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.

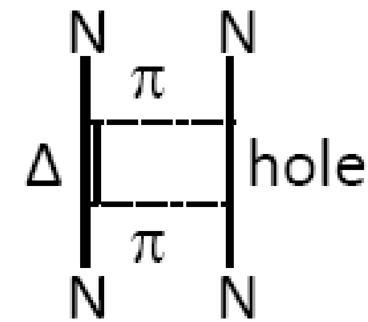


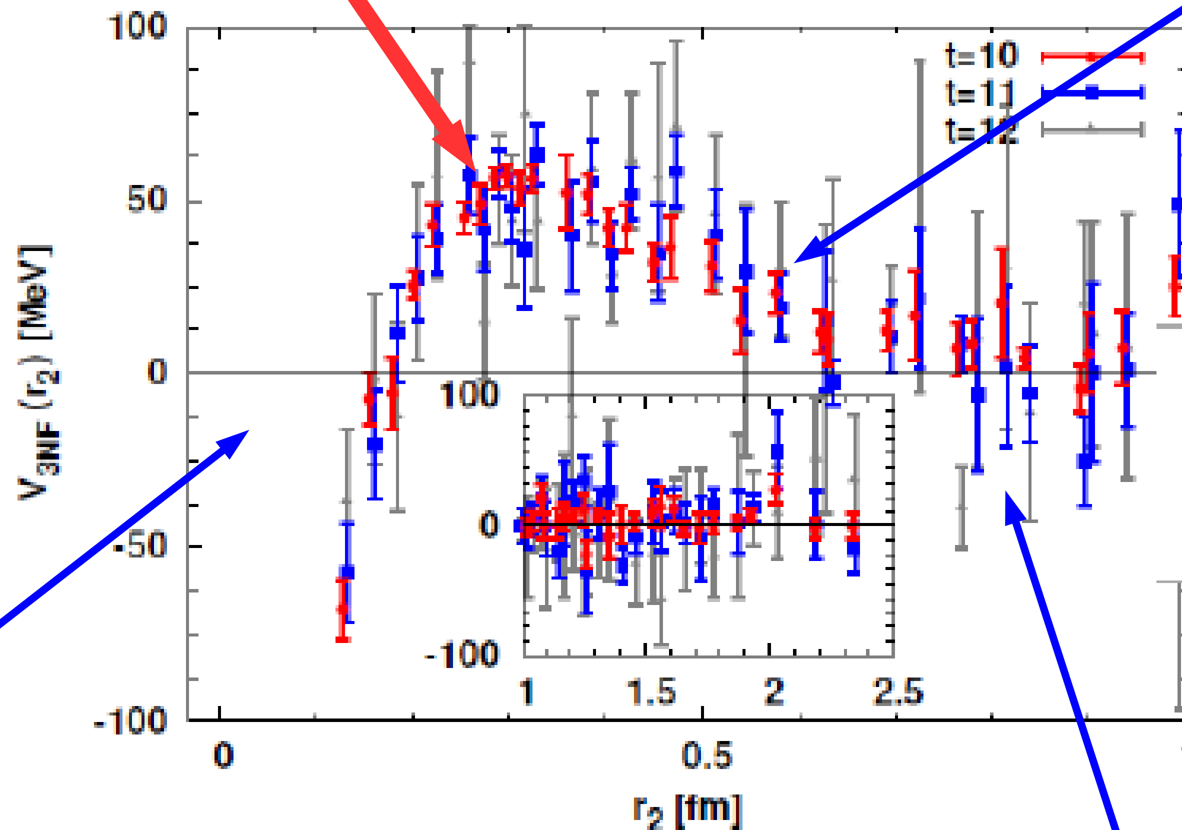
Fujiwara, Suzuki, Nakamoto ('07)

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

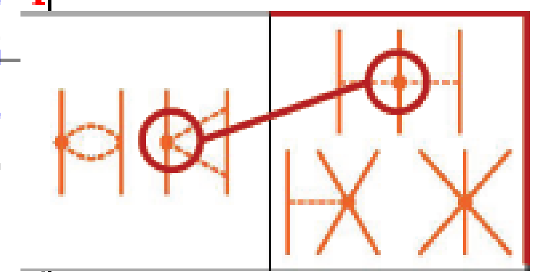
Three-Baryon force

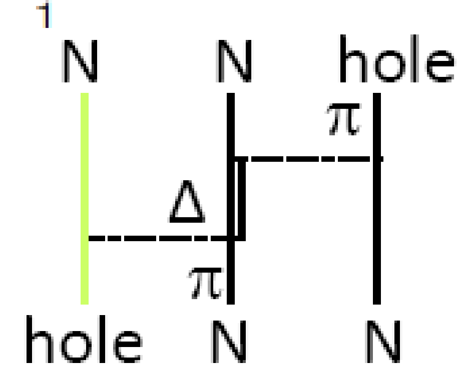
What makes 3B repulsion at r ~ 0.5 fm ?





pQCD





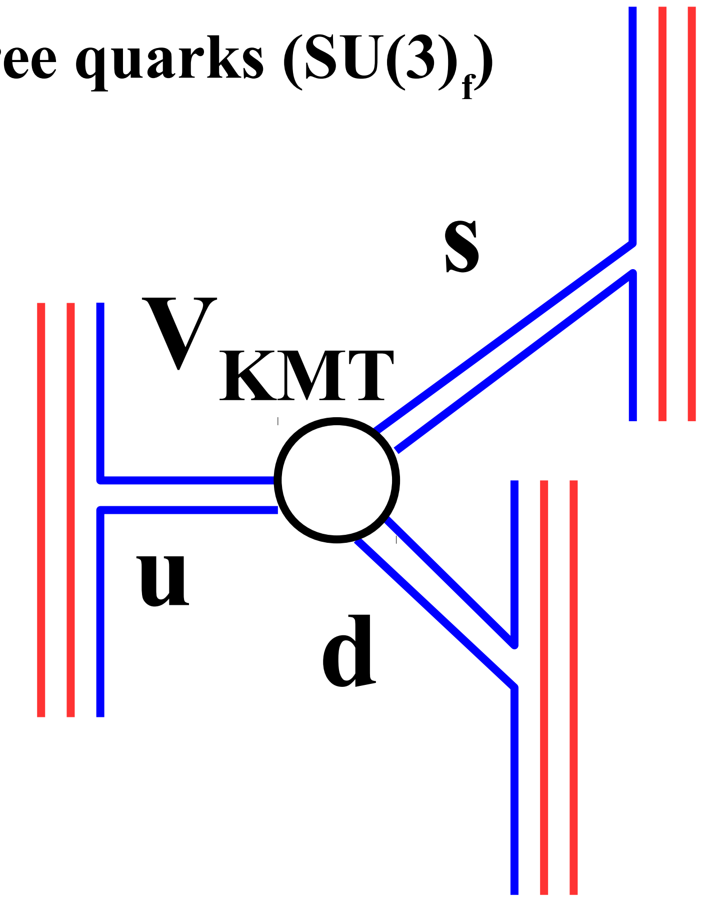
Taken from NPCSM 2016 talks,
Doi (Wed), Kohno (Thu), Tews (Thu)

Kobayashi-Maskawa-'t Hooft (KMT) interaction

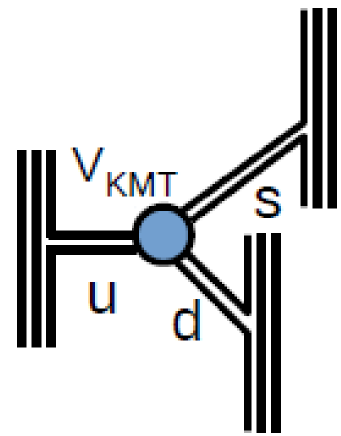
- **KMT interaction** *Kobayashi, Maskawa ('70), 't Hooft ('76)*

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

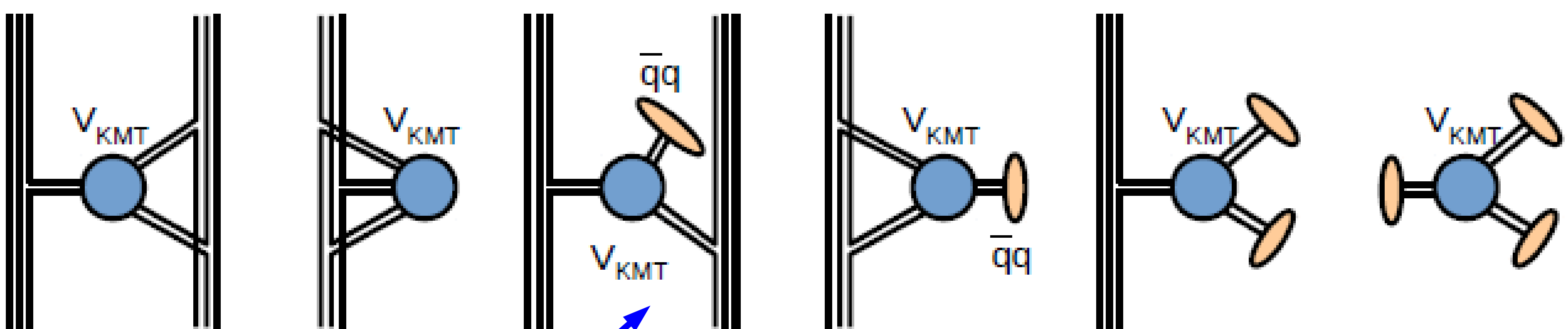
- **Determinant interaction in flavor for three quarks (SU(3)$_f$)**
- **Responsible for U(1)$_A$ anomaly**
  η-η' mass diff.
  → g_D= – 9.29 *Hatsuda, Kunihiro ('94)*
  – 12.36 *Rehberg, Klevanski, Hufner ('96)*
- **KMT interaction should generate 2B and 3B interaction when hyperons are involved.**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

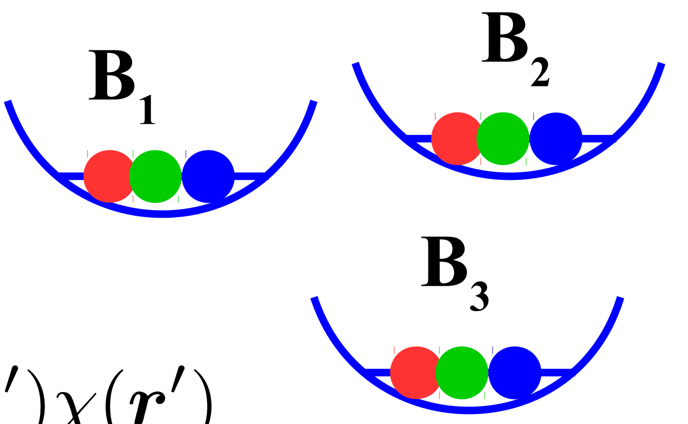
quark mass, vac. E.
(Hatsuda, Kunihiro)

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 χ) >> (baryon size),**

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

Norm Kernel

- **Antisymmetrizer makes the calculation complicated !**

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

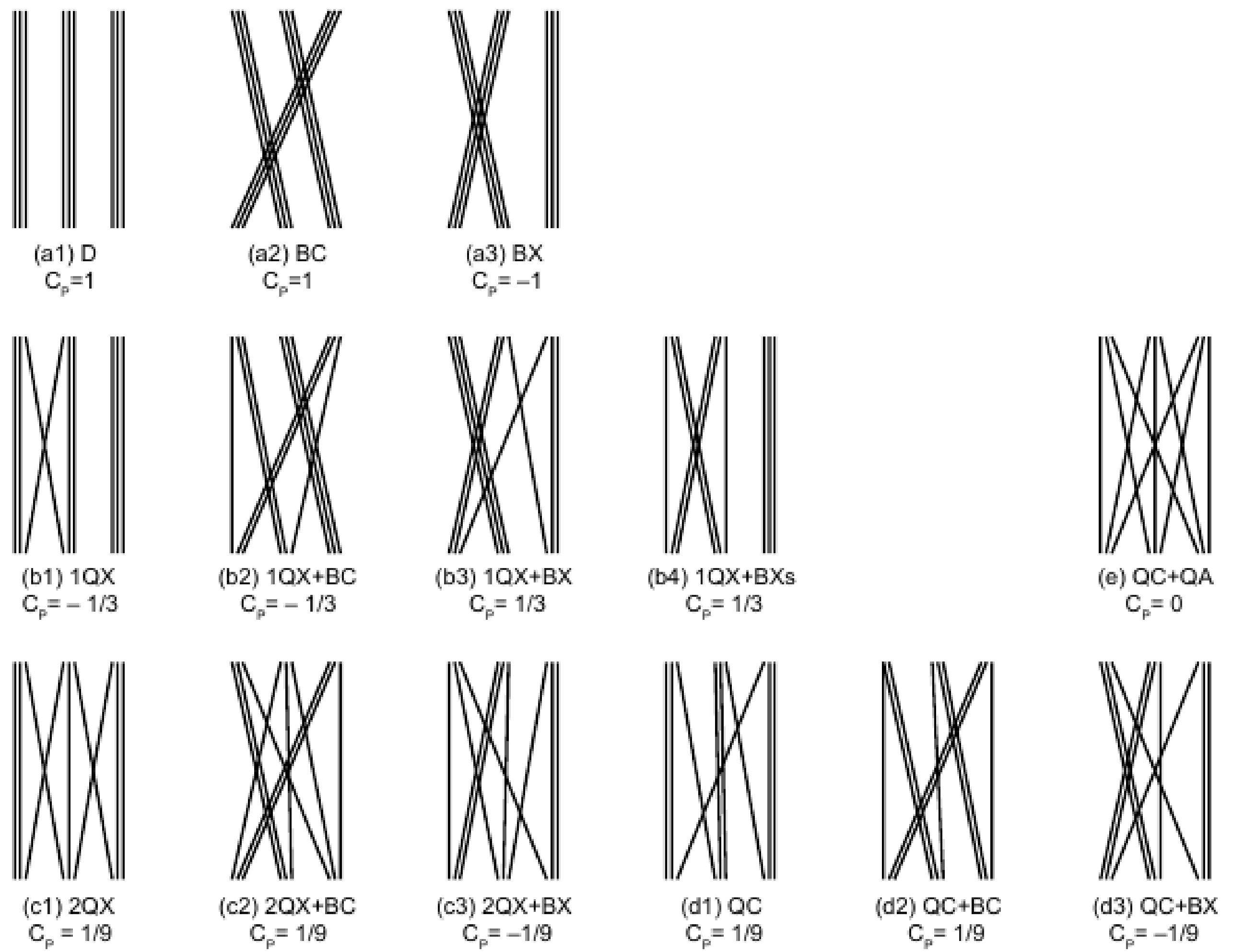
$$\mathcal{A}_B = \sum_{\mathcal{P}} (-1)^{\pi(\mathcal{P})}\,\mathcal{P}$$

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 barvon 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

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

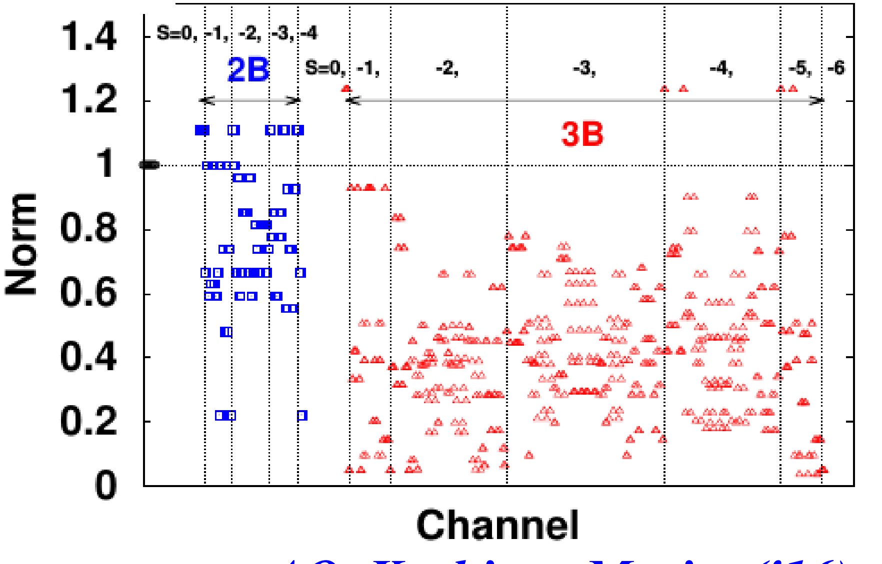
$$C_P = -\frac{1}{(3!)^2}\varepsilon_{abd}\varepsilon_{cef}\varepsilon_{abc}\varepsilon_{def} = -\frac{1}{36}\,2\delta_{dc}\,2\delta_{cd} = -\frac{1}{3}$$

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

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

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

- **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

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

irrelevant quarks

product w.f.

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

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

flavor matching (numerical)

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

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

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

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

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
$N_\uparrow\Lambda_\uparrow, N_\downarrow\Lambda_\downarrow$	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	$12/3$
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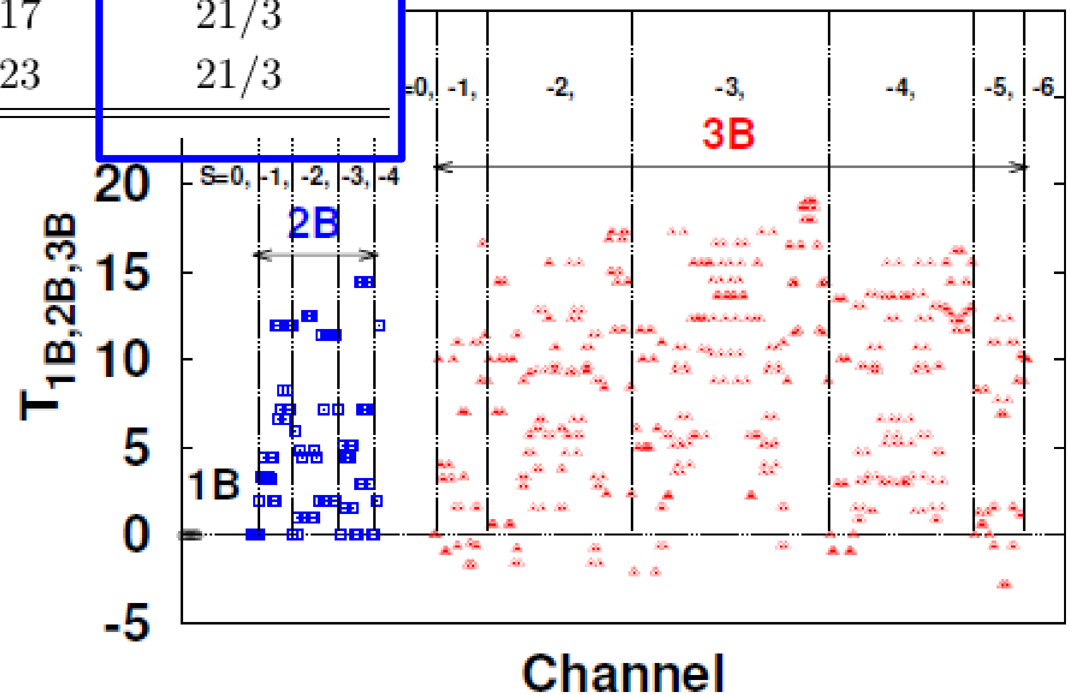
$N\Lambda_\uparrow\Lambda_\downarrow$	$45/54$	$1035/54$	23	$21/3$

Big for npΛ (S=3/2)



KMT matrix elements strongly depend on the channel

3B potential from KMT interaction

- **3q int. → 3B potential**

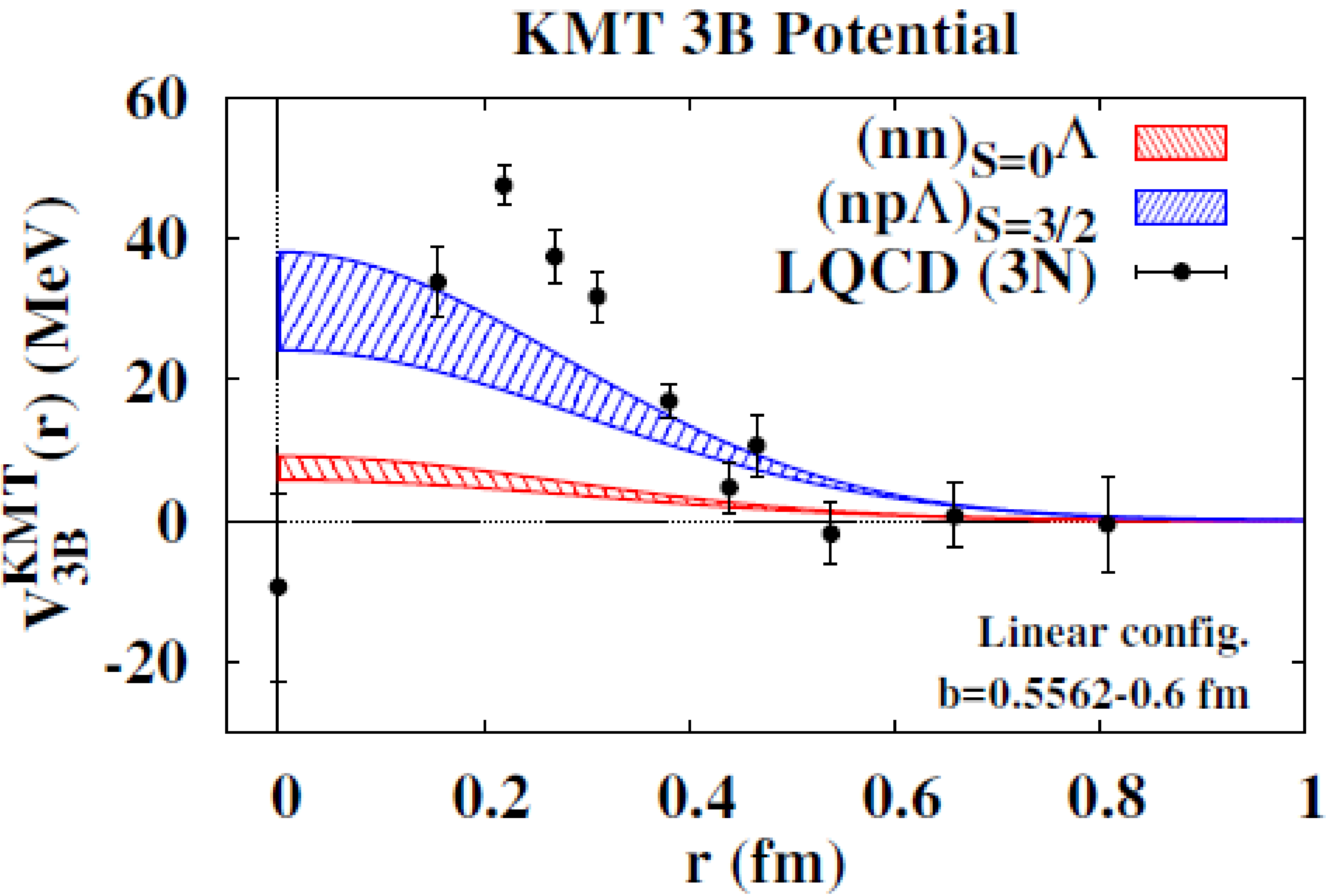
$$V_{3B}^{KMT} = -2 g_D T_{3B} \int d^3x \varphi^*_{R_a}(x)\varphi^*_{R_b}(x)\varphi^*_{R_c}(x)\varphi_{R_d}(x)\varphi_{R_e}(x)\varphi_{R_f}(x)$$

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

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

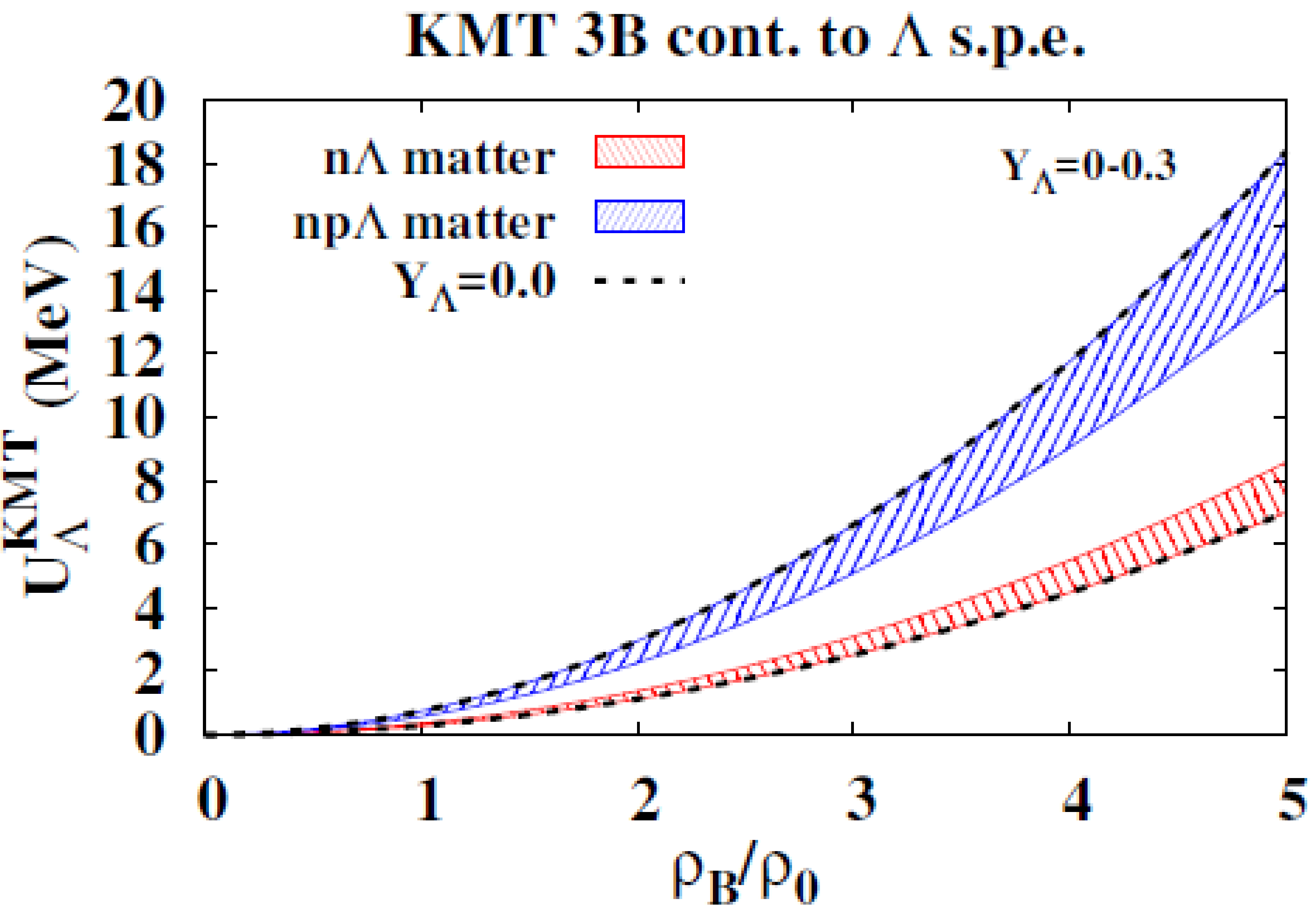
Parameters are taken from
Hatsuda, Kunihiro ('94), Rehberg, Klevanski, Hufner ('96), Fujiwara, Suzuki, Nakamoto ('07), Oka, Yazaki ('81)

3B potential from KMT interaction



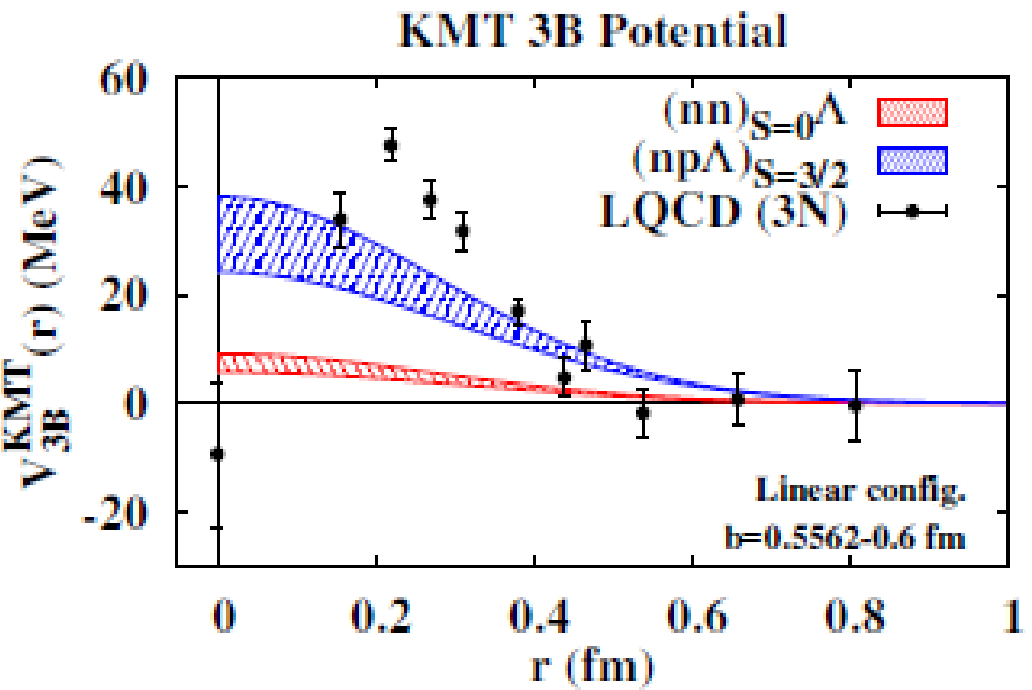
Lattice data: Doi et al. (HAL QCD) ('07)

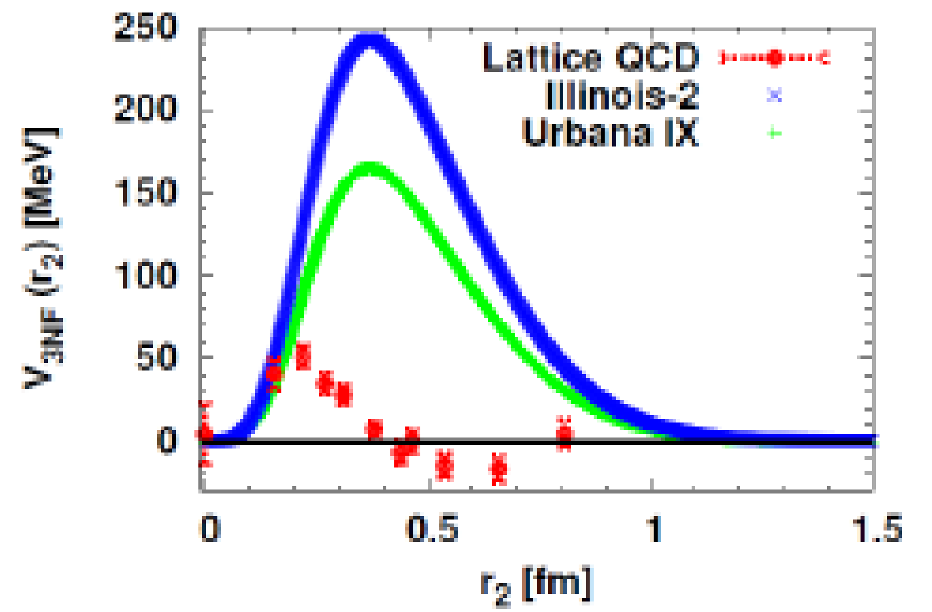
KMT-3B Contribution to Λ potential



Density is assumed to be uniform. No correlation effects.

3B potential from KMT: Repulsive enough ?





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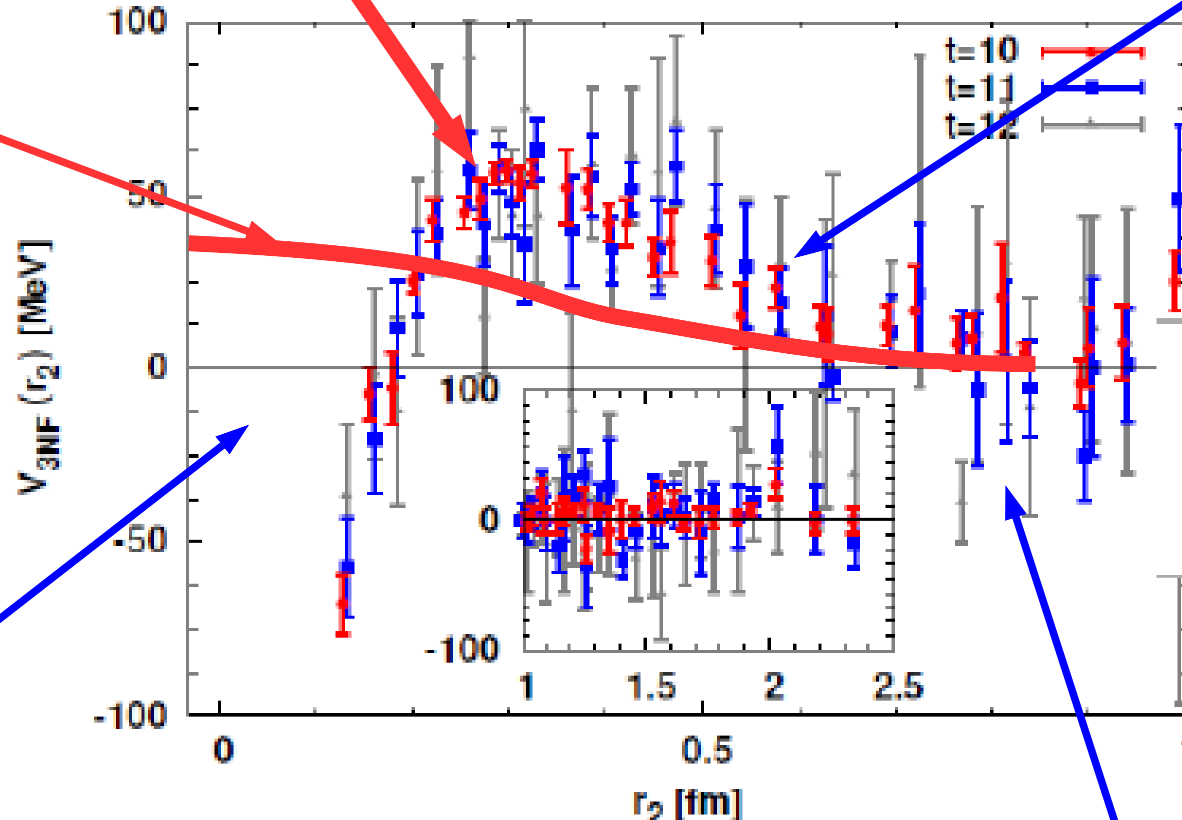
Summary

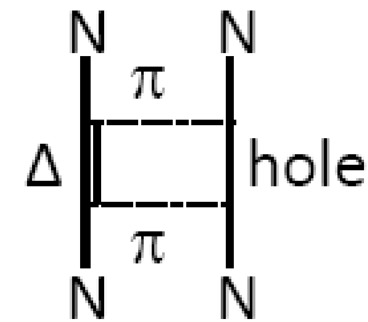
- Quark model three-baryon (3B) potential may be a promising method to evaluate the 3B potential at short distances.
- Kobayashi-Maskawa-'t Hooft (KMT) interaction generates 3q potential among u,d,s quarks, and generates 3B potential only when hyperons are involved.
- Expectation value of the KMT interaction 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.

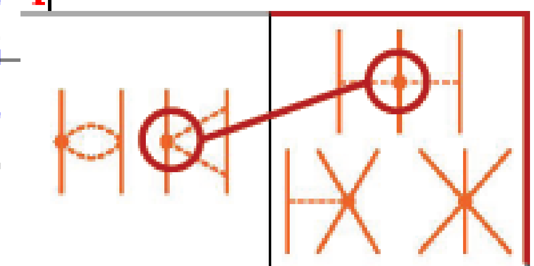
Three-Baryon force

What makes 3B repulsion at r ~ 0.5 fm ?

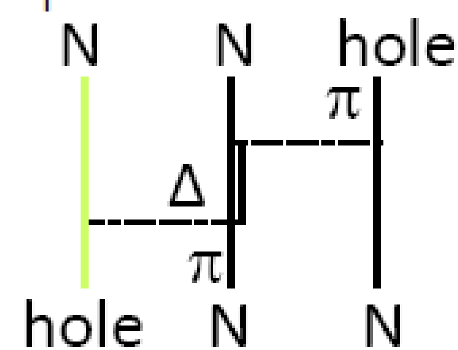
KMT
(ΛNN)





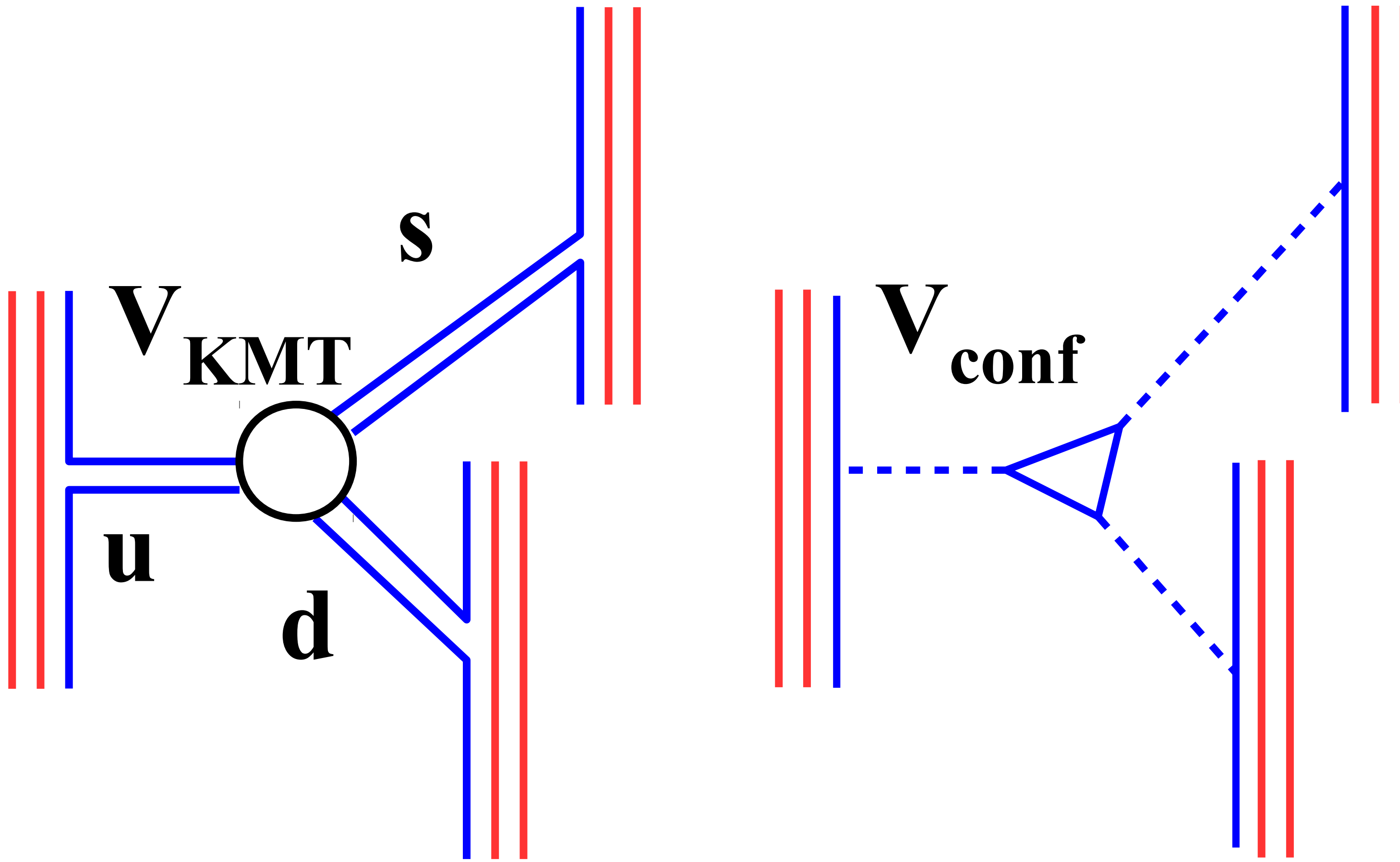


pQCD



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

Confinement Potential → 3B Potential ?



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

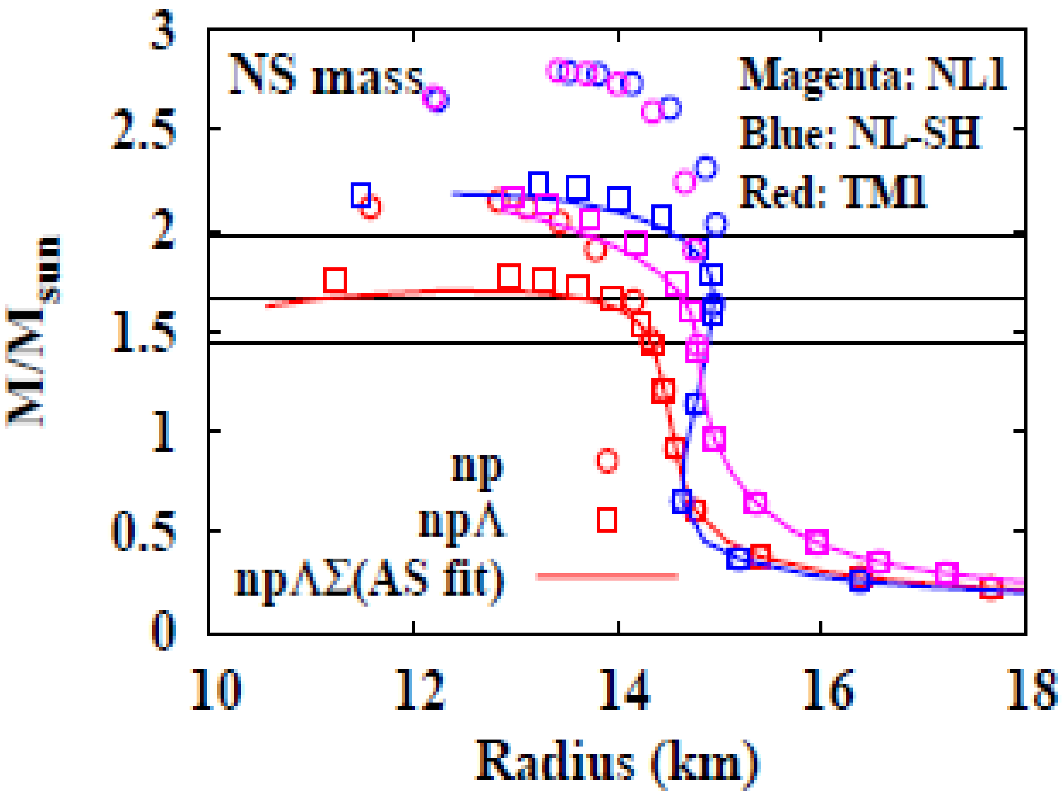
Takahashi, Suganuma, Nemoto, Matsufuru ('02)

Thank you for your attention !

Massive Neutron Stars with Hyperons

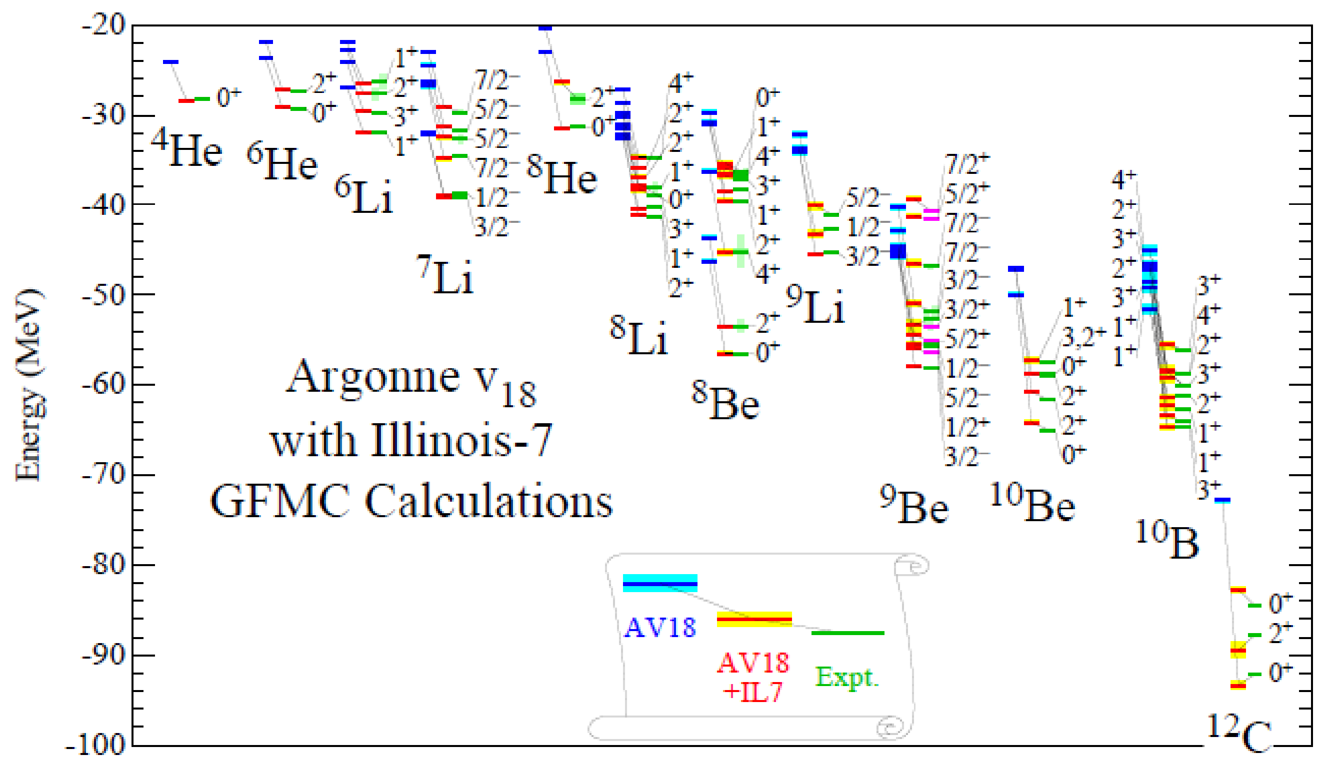
Tsubakihara, Harada, AO, arXiv:1402.0979

- **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, $\Lambda\Lambda$ 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)**

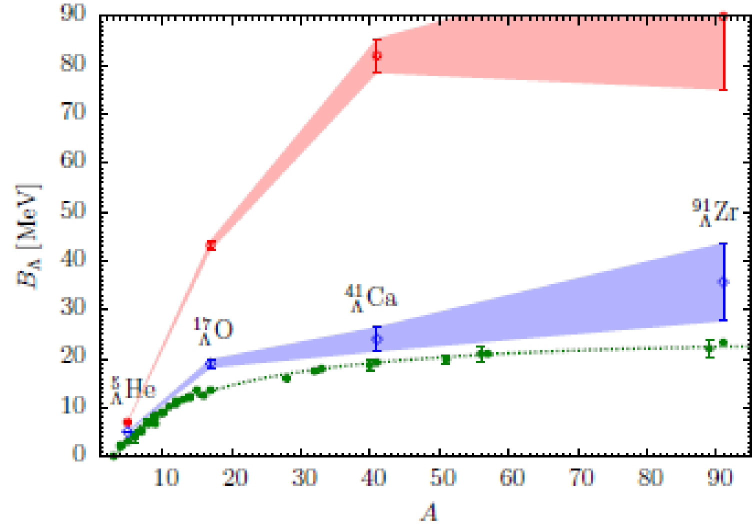


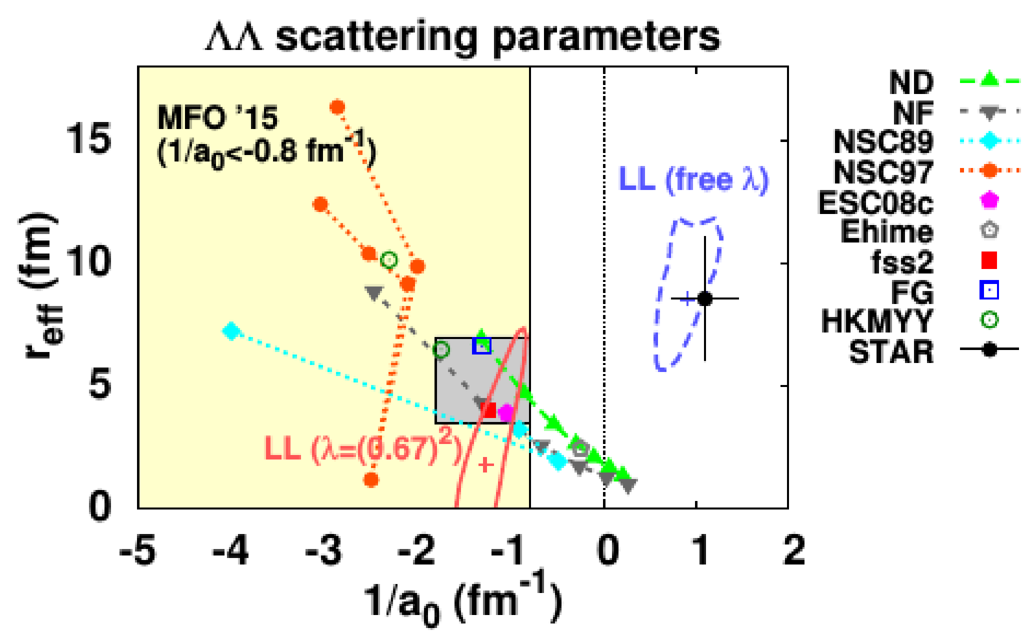
J. Carlson et al. ('14)

YITP YUKAWA INSTITUTE FOR THEORETICAL PHYSICS
Neutron Star Matter

3BF including Hyperons

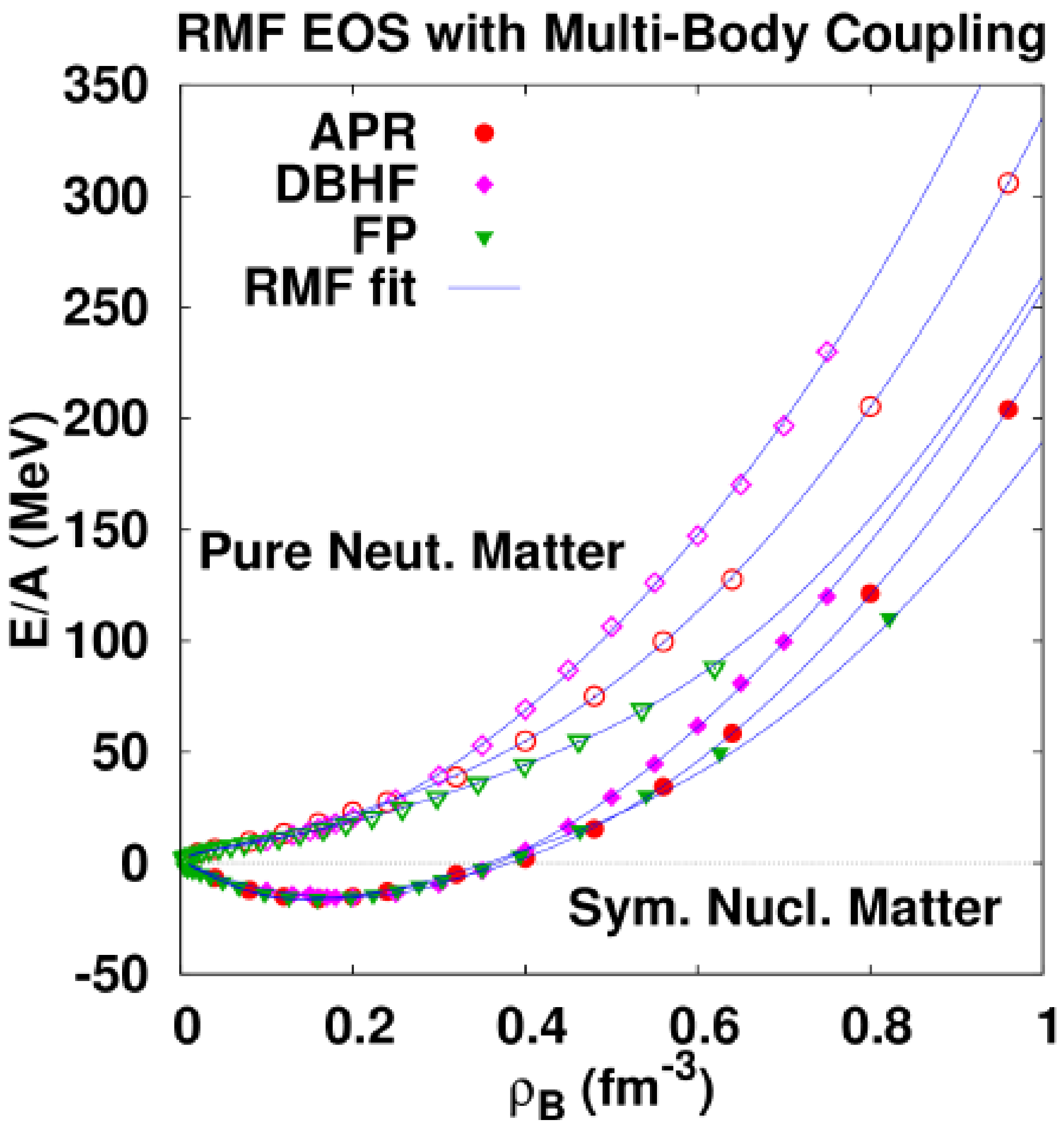
- **3BF incl. YNN, YYN and YYY should exist and contribute to EOS.**
  Nishizaki, Takatsuka, Yamamoto ('02)
  - **Chiral EFT, Multi-Pomeron exch., Quark Pauli, Lattice 3BF, SJ, ..**
    Kohno('10); Heidenbauer+('13); Yamamoto+('14); Nakamoto, Suzuki; Doi+(HALQCD,'12); Tamagaki('08); …
  - **Quant. MC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



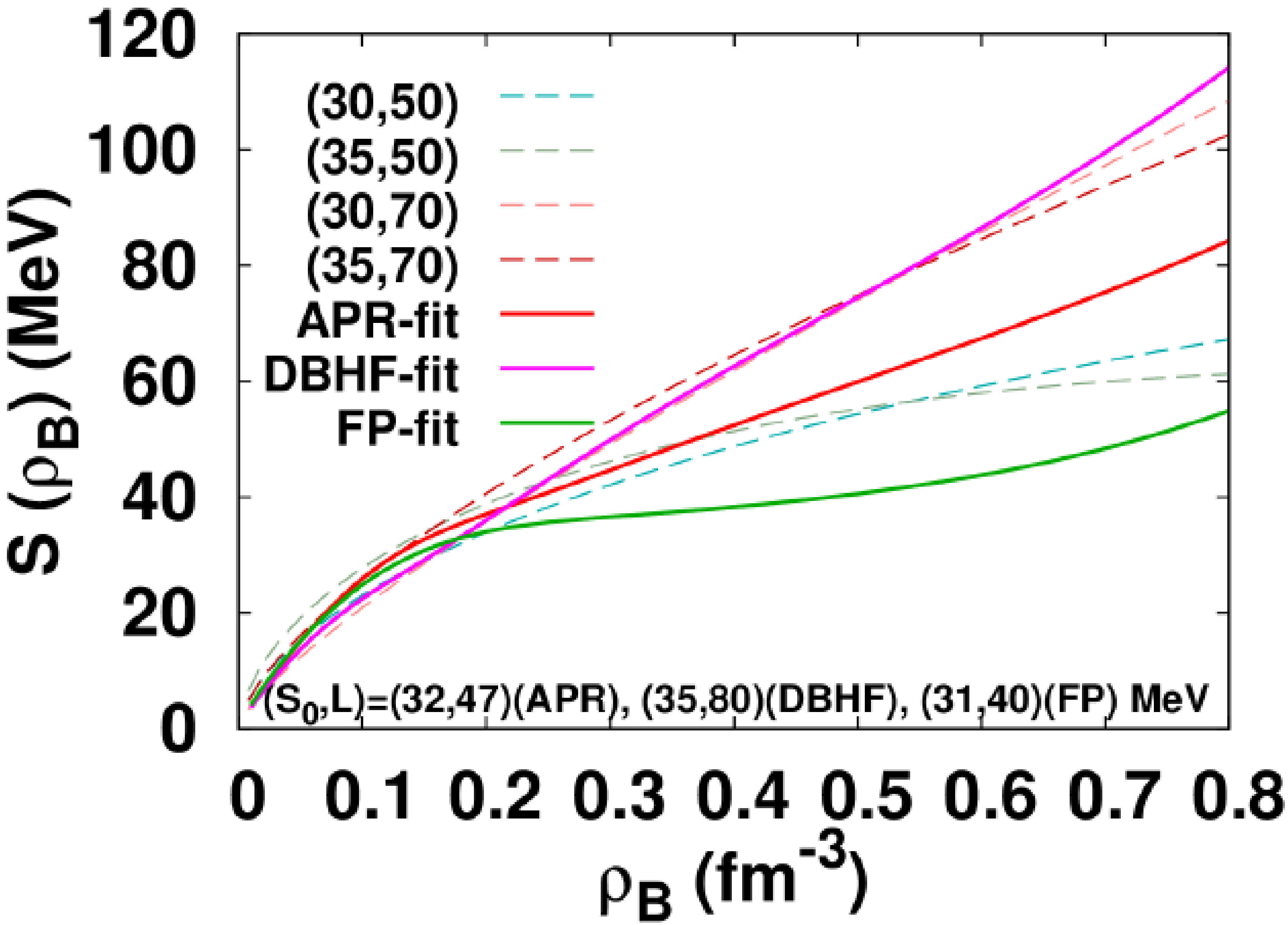


Caveat: Missing data

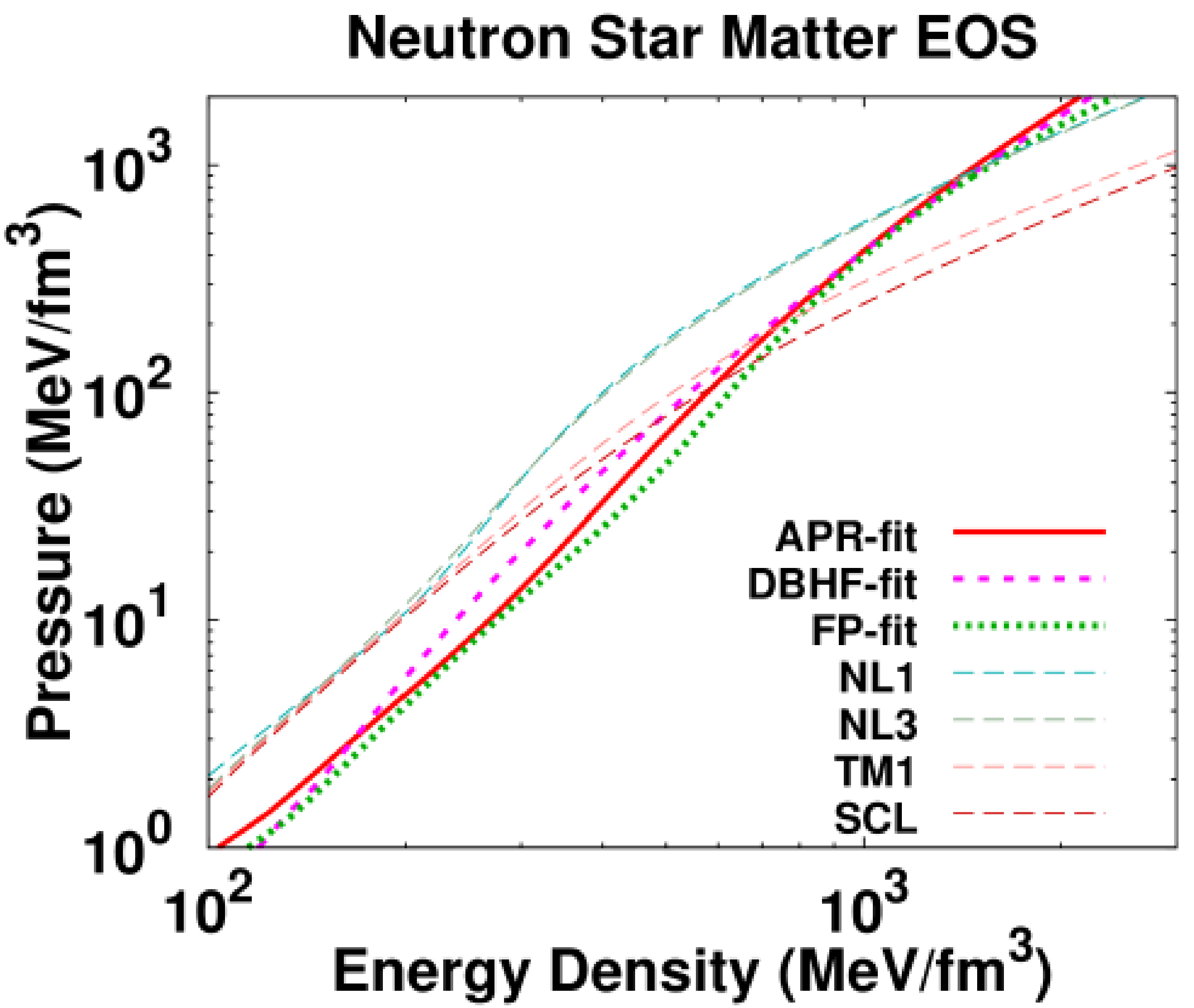
Fitting "Ab initio" EOS via RMF

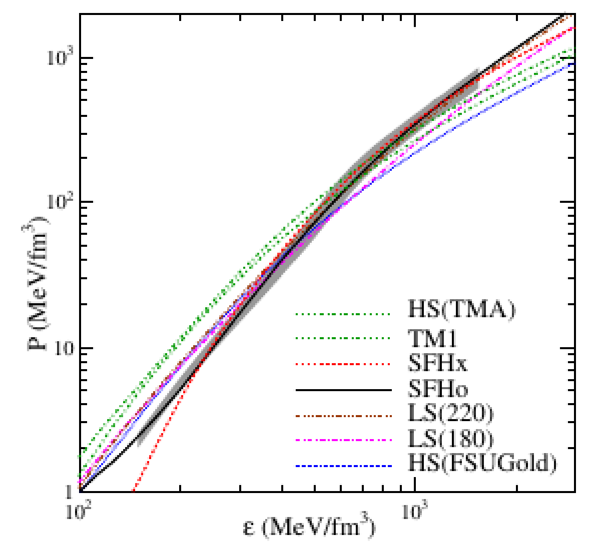


Symmetry Energy



Neutron Star Matter EOS

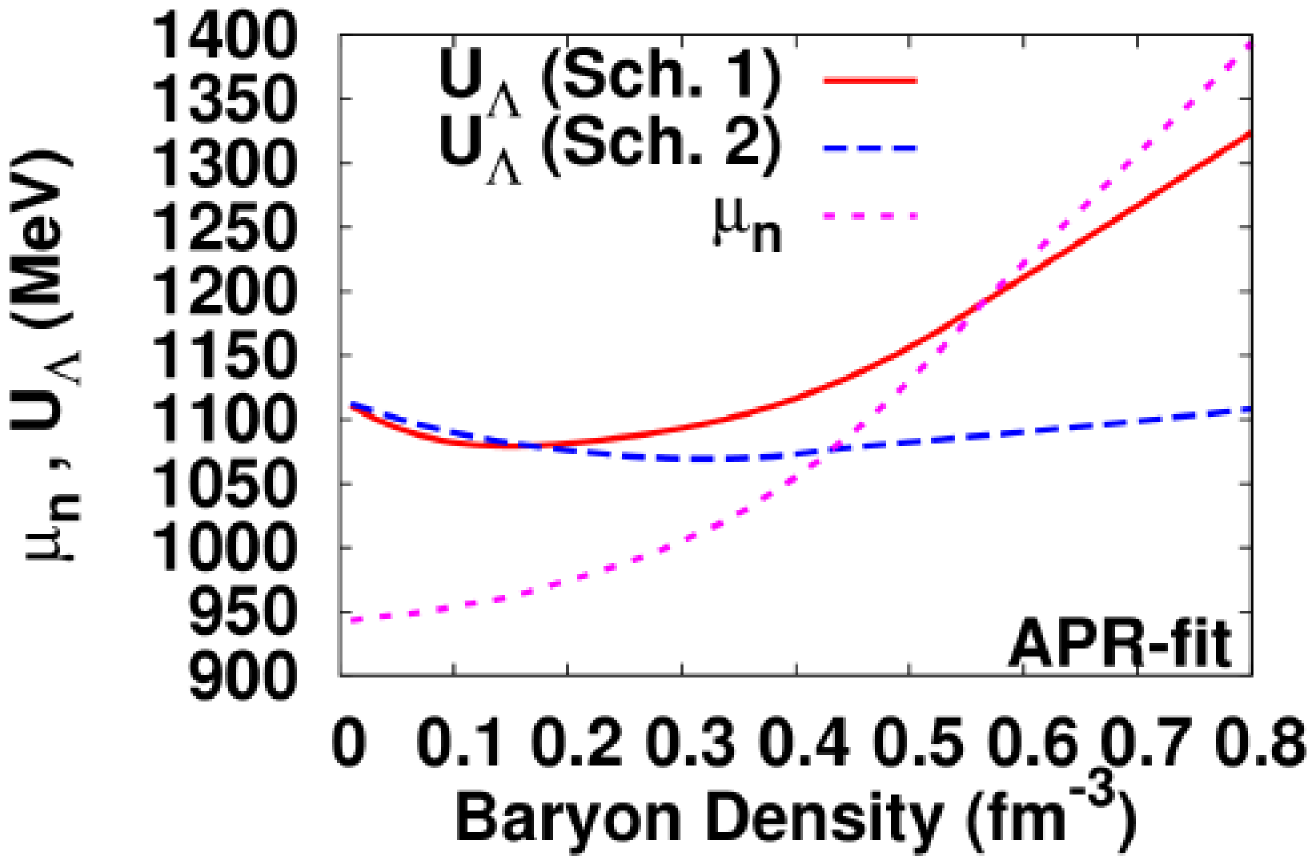




A. W. Steiner, M. Hempel, T. Fischer, ApJ 774 (2013) 17 (TMA+NSE w/ excl. vol.)

NS matter in "ab initio"-fit + Λ

- Λ potential in nuclear matter at $\rho_0 \sim -30$ 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