Strongly Tensor Correlated Hartree-Fock Theory

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In collaboration with

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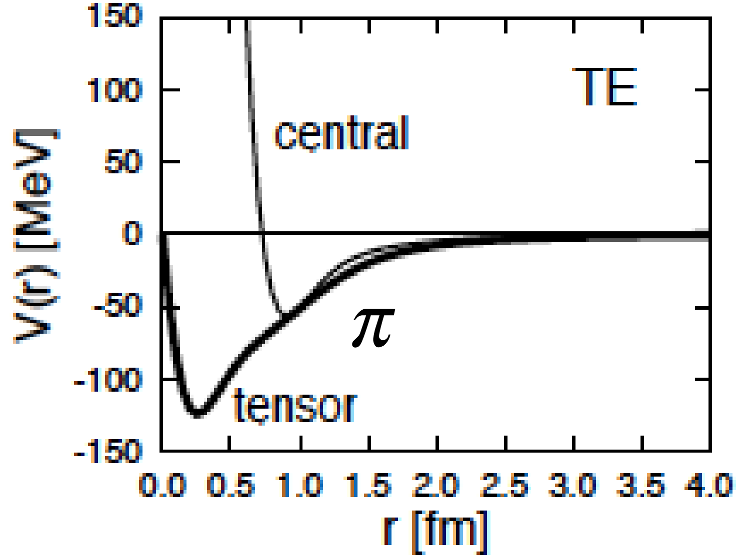
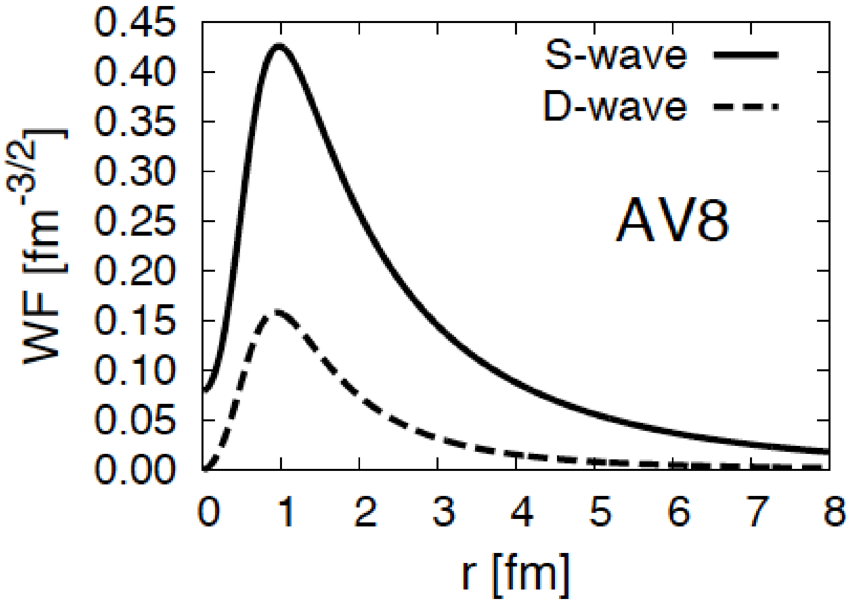
Content

- Importance of pion in light nuclei
- Tensor optimized shell model (TOSM)
  0p0h + 2p2h states
- Strongly tensor correlated Hartree-Fock theory
- Delta for three-body interaction
- Nuclear URCA process
- Conclusion

The importance of pion is clear in deuteron

NN interaction





enso

S=1 and L=0 or 2

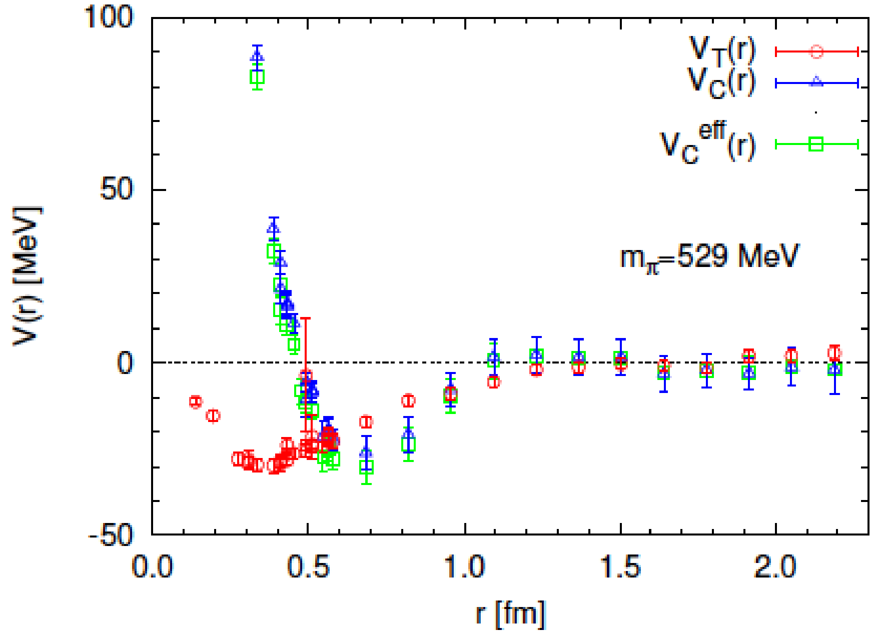
Deuteron (1^+)

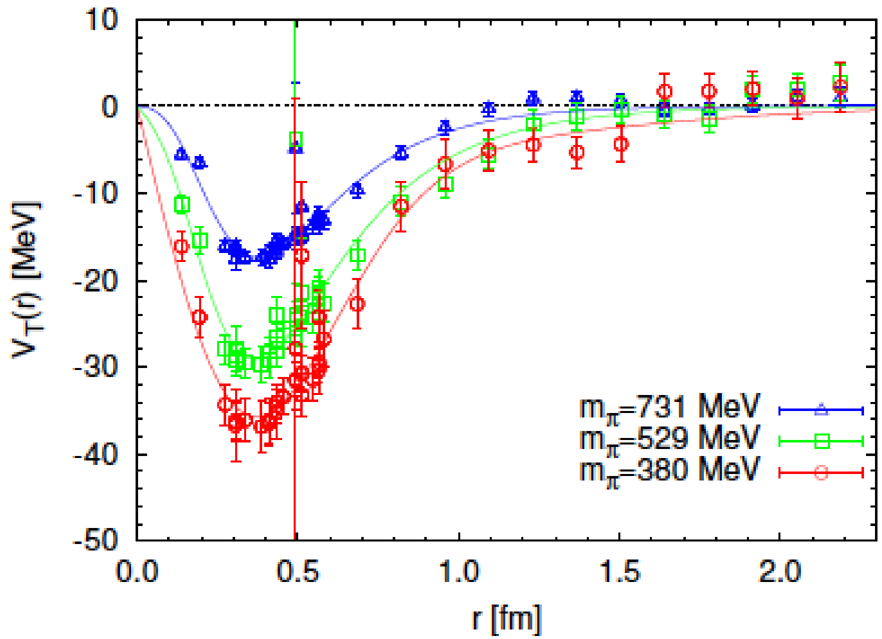
Energy	−2.24 [MeV]
Kinetic	19.88
(SS)	11.31
(DD)	8.57
Central	−4.46
(SS)	−3.96
(DD)	−0.50
Tensorc	−16.64
(SD)	−18.93
(DD)	2.29
LS	−1.02
P(*D*)	5.78 [%]
Radius	1.96 [fm]
(SS)	2.00 [fm]
(DD)	1.22 [fm]

Progress of Theoretical Physics, Vol. 123, No. 1, January 2010

Theoretical Foundation of the Nuclear Force in QCD and Its Applications to Central and Tensor Forces in Quenched Lattice QCD Simulations

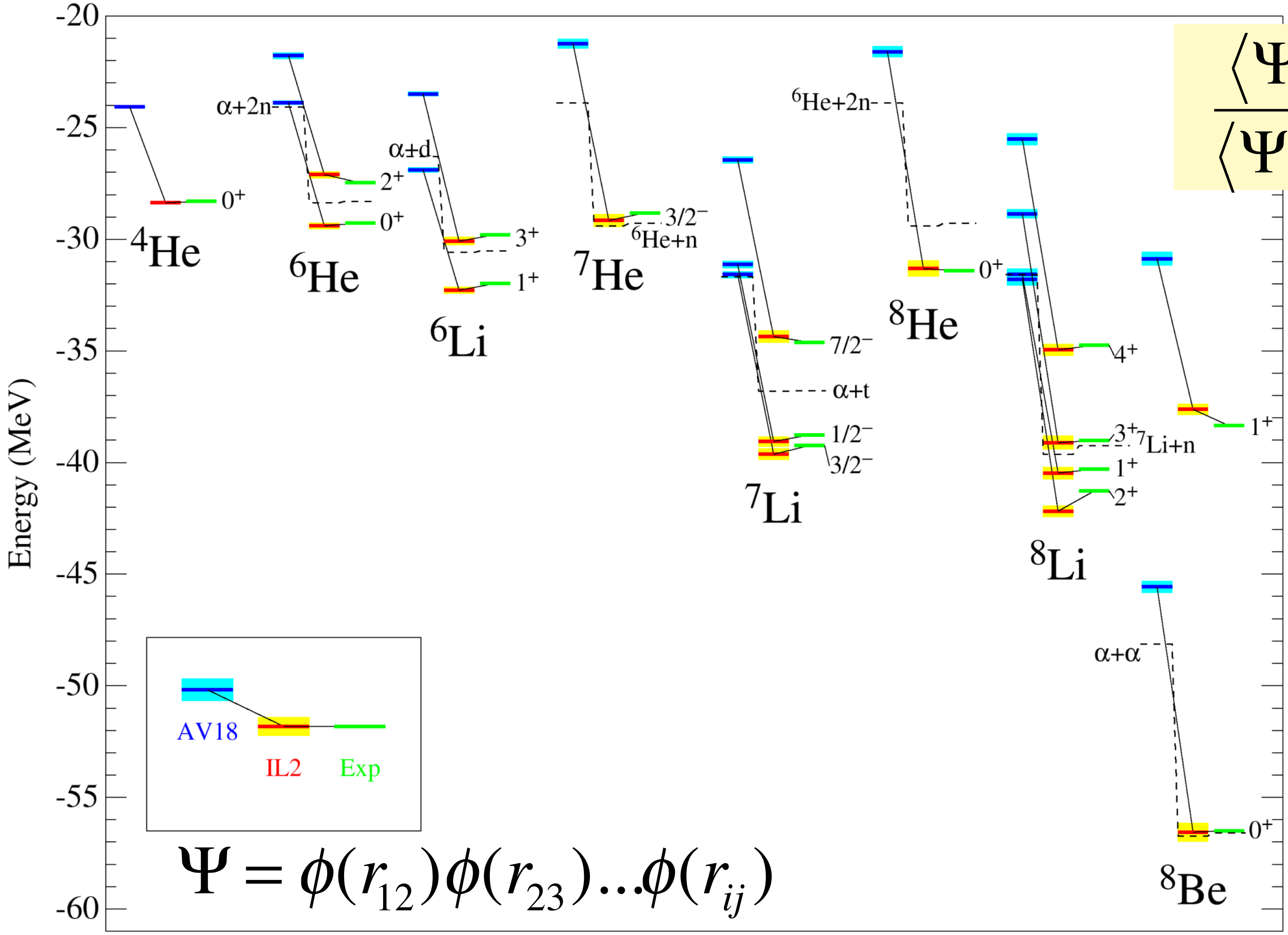
Sinya AOKI,[1] Tetsuo HATSUDA[2] and Noriyoshi ISHII[2]





Variational calculation of few body system with NN interaction

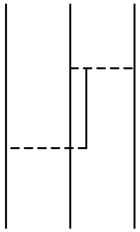
VMC+GFMC



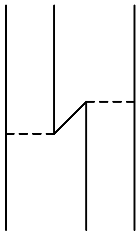
$$\frac{\langle\Psi|V_\pi|\Psi\rangle}{\langle\Psi|V_{NN}|\Psi\rangle} \sim 80\%$$

$$\Psi = \phi(r_{12})\phi(r_{23})\ldots\phi(r_{ij})$$

V_{NNN}



Fujita-Miyazawa



Relativistic

C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci.51(2001)

Heavy nuclei (Super model)

Pion is key

Pion is important in nucleus

- 80% of attraction is due to pion
- Tensor interaction is particularly important

Pion	Tensor	spin-spin

$$\frac{\vec{\sigma}_1 \cdot \vec{q}\,\vec{\sigma}_2 \cdot \vec{q}}{m_\pi^2 + q^2} = \frac{1}{3}\frac{q^2}{m_\pi^2 + q^2} S_{12}(\hat{q}) + \frac{1}{3}\frac{q^2}{m_\pi^2 + q^2}\vec{\sigma}_1 \cdot \vec{\sigma}_2$$

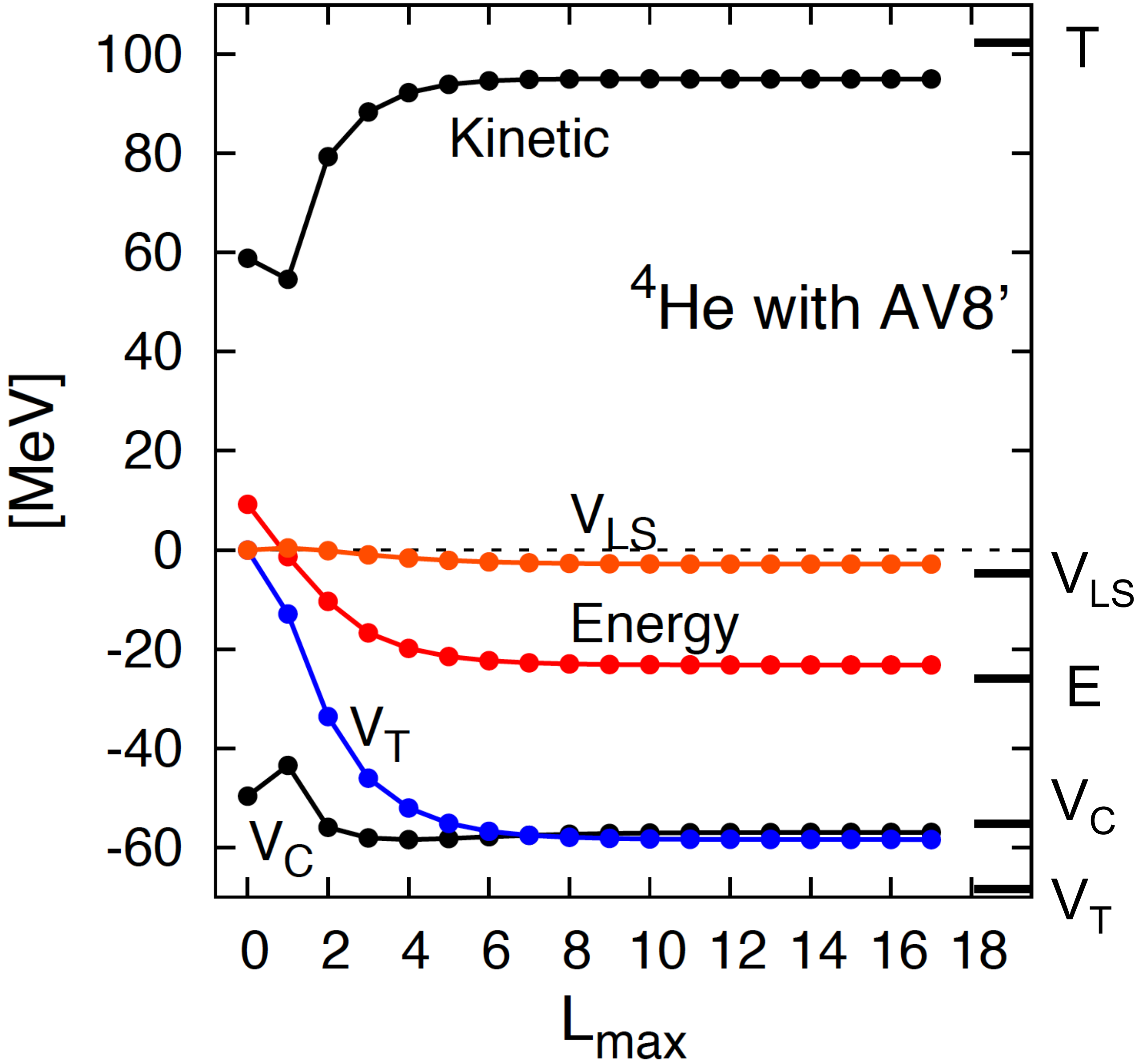
$$= \frac{1}{3}\frac{q^2}{m_\pi^2 + q^2} S_{12}(\hat{q}) + \frac{1}{3}\left(\cancel{1} - \frac{m_\pi^2}{m_\pi^2 + q^2}\right)\vec{\sigma}_1 \cdot \vec{\sigma}_2$$

$$S_{12}(\hat{q}) = \sqrt{\frac{24\pi}{5}}\left[Y_2(\hat{q})\left[\sigma_1\sigma_2\right]_2\right]_0$$

TOSM+UCOM with AV8'

$$\Psi = C_0 |0\rangle + \sum_\alpha C_\alpha |2p2h:\alpha\rangle$$

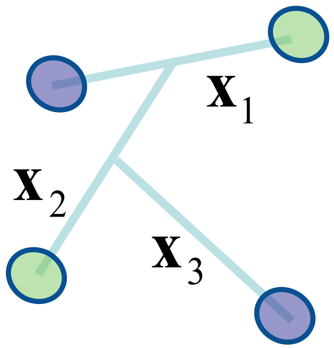
Myo Toki Ikeda
PTP (2009)



Few body
Calculation
(Kamda et al)

Tensor Optimized Few-body Model (TOFM)

Horii Toki Myo Ikeda: PTP (2012)

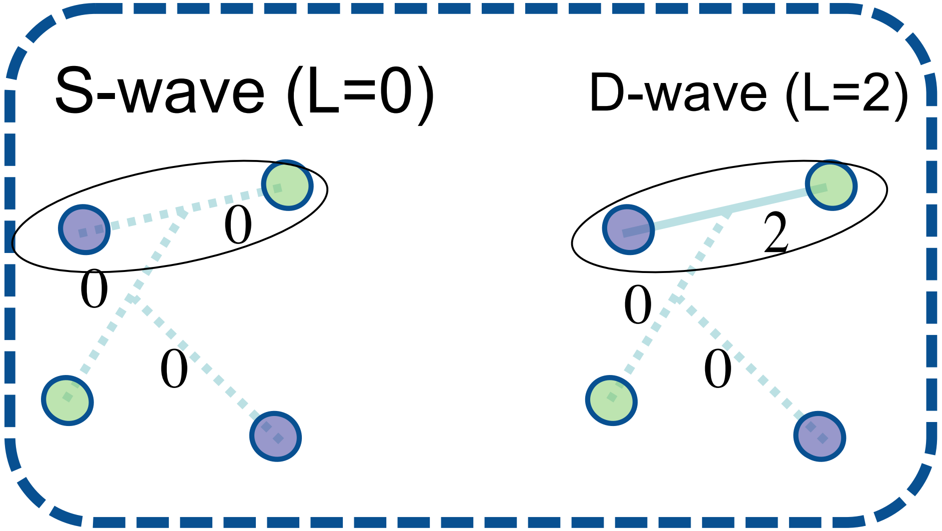


Jacobi coordinate x_1, x_2, x_3

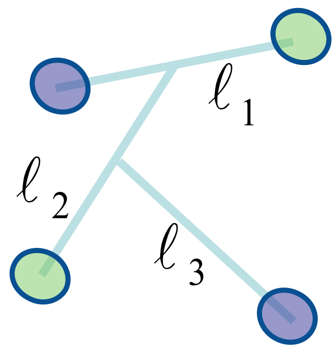
$$|\Psi\rangle = |\Psi\rangle_S + |\Psi\rangle_D \qquad \langle D|S_{12}|S\rangle \neq 0$$

$$|\Psi\rangle_{S,D} = \sum_{i=1}^{k} c_i \psi_i = \sum_{i=1}^{k} c_i \mathcal{A}\left[\psi_L^{space} \chi_S^{spin}\right]_J \chi_T^{isospin}$$

For ^{4}He Total J=0, S-wave (L=0,S=0)
D-wave(L=2,S=2)

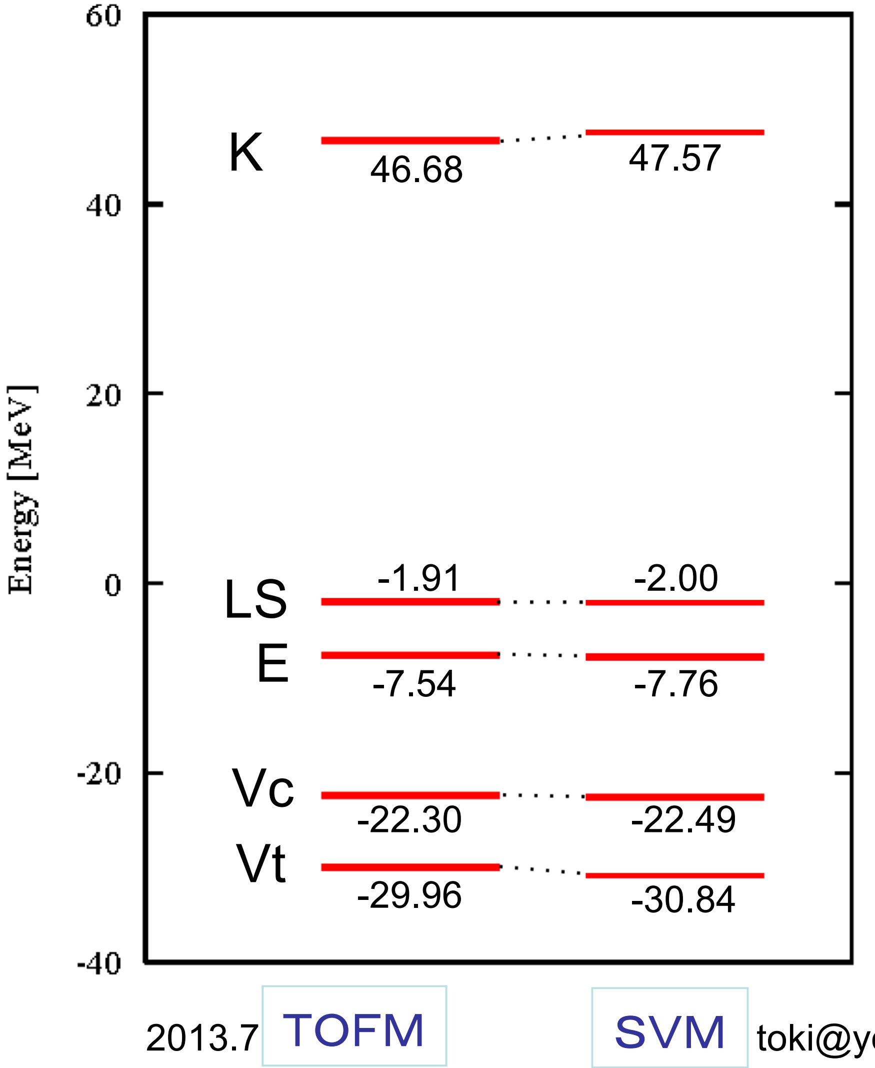


$$l_1 \neq l_2 \neq l_3 = any$$

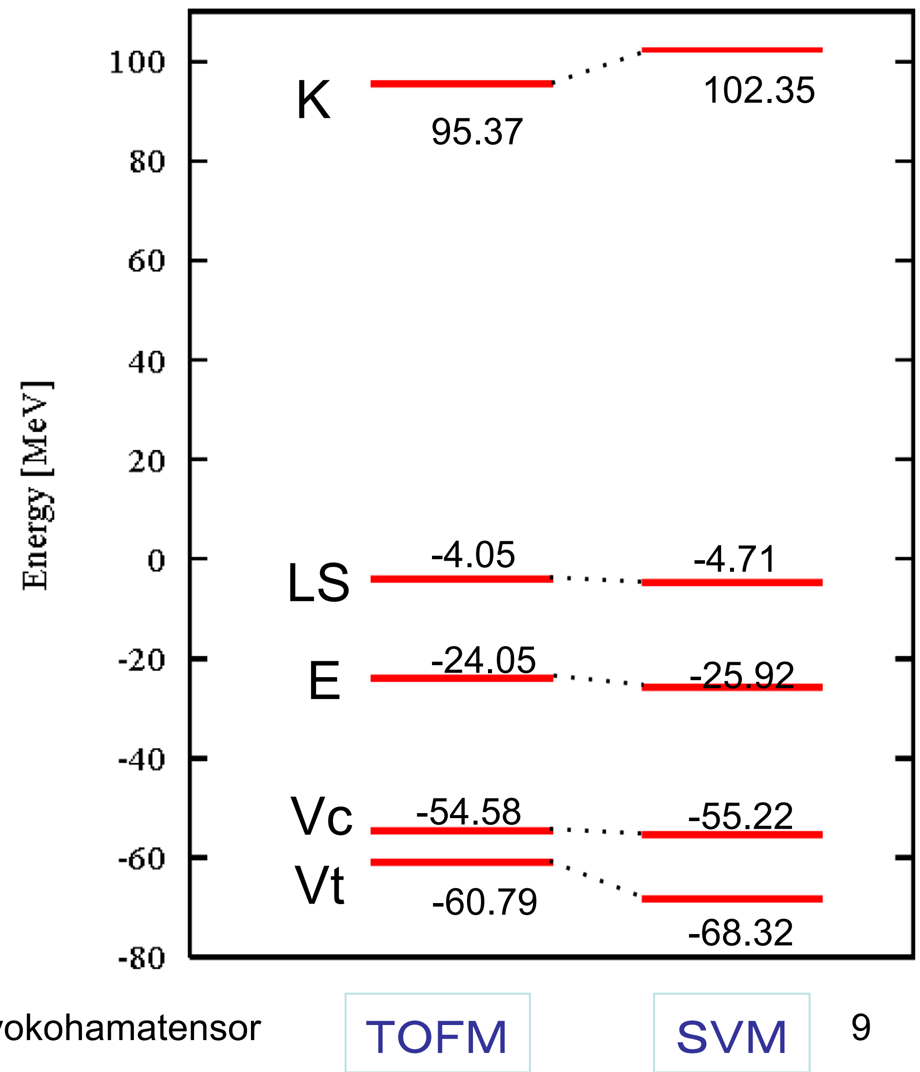


Comparison of TOFM with rigorous calculation (SVM)

^{3}H with AV8'



^{4}He with AV8' (w/o Coulomb)



Extended Brueckner–Hartree–Fock theory with pionic correlation in finite nuclei

Yoko Ogawa *, Hiroshi Toki

Annals of Physics (2011)

Super model

$$\langle 0|S_{12}|0\rangle = 0, \qquad S_{12} = \sqrt{\frac{24\pi}{5}}[Y_2(\hat{r}) \times [\sigma_1 \times \sigma_2]_2]^{(0)}.$$

We cannot treat the tensor interaction in HF space.

$$|\Psi\rangle = C_0|0\rangle + \sum_\alpha C_\alpha |2p-2h:\alpha\rangle$$

$$\delta\frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle} = 0 \qquad \langle\Psi|\Psi\rangle = |C_0|^2 + \sum_\alpha |C_\alpha|^2 = 1$$

Total energy

$$\langle \Psi | H | \Psi \rangle = |C_0|^2 \langle 0 | H | 0 \rangle + C_0^* \sum_\alpha C_\alpha \langle 0 | H | 2p - 2h : \alpha \rangle$$
$$+ C_0 \sum_\alpha C_\alpha^* \langle 2p - 2h : \alpha | H | 0 \rangle + \sum_{\alpha\beta} C_\alpha^* C_\beta \langle \alpha | H | \beta \rangle$$

$$|2p - 2h : \alpha \rangle \equiv |\alpha\rangle$$

Variational principle

$$\frac{\partial}{\partial C_\alpha^*} \langle \Psi | H - E | \Psi \rangle = 0$$

$$C_0 \langle \alpha | H | 0 \rangle + \sum_\beta C_\beta \langle \alpha | H | \beta \rangle = E C_\alpha$$

$$\frac{\partial}{\partial \psi_a^*(x)} \left[\langle \Psi | H | \Psi \rangle - \sum_b e_b \psi_b^*(x) \psi_b(x) \right] = 0$$

$$|0\rangle = \prod_a \psi_a(x)$$

$$|C_0|^2 \frac{\partial}{\partial \psi_a^*} \langle 0 | H | 0 \rangle + C_0^* \sum_\alpha C_\alpha \frac{\partial}{\partial \psi_a^*} \langle 0 | H | \alpha \rangle + \sum_{\alpha\beta} C_\alpha^* C_\beta \frac{\partial}{\partial \psi_a^*} \langle \alpha | H | \beta \rangle = e_a \psi_a(x)$$

Comparison of BHF and STCHF

$$(T+V)\psi = E\psi$$

$$G = V - V\frac{Q}{T-(E_1+E_2)}G$$

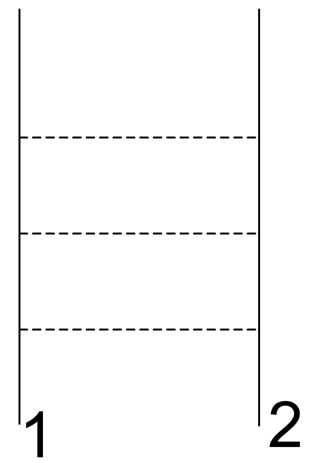
$$G = V - V\frac{Q}{H_{HF} - E^h_{HF} + V}V$$

$$\langle 0|T+G|0\rangle = \langle 0|T+V|0\rangle - \sum_{\alpha\beta}\langle 0|V|\alpha\rangle\langle\alpha|\frac{1}{H_{HF}-E^h_{HF}+V}|\beta\rangle\langle\alpha|V|0\rangle$$

STCHF

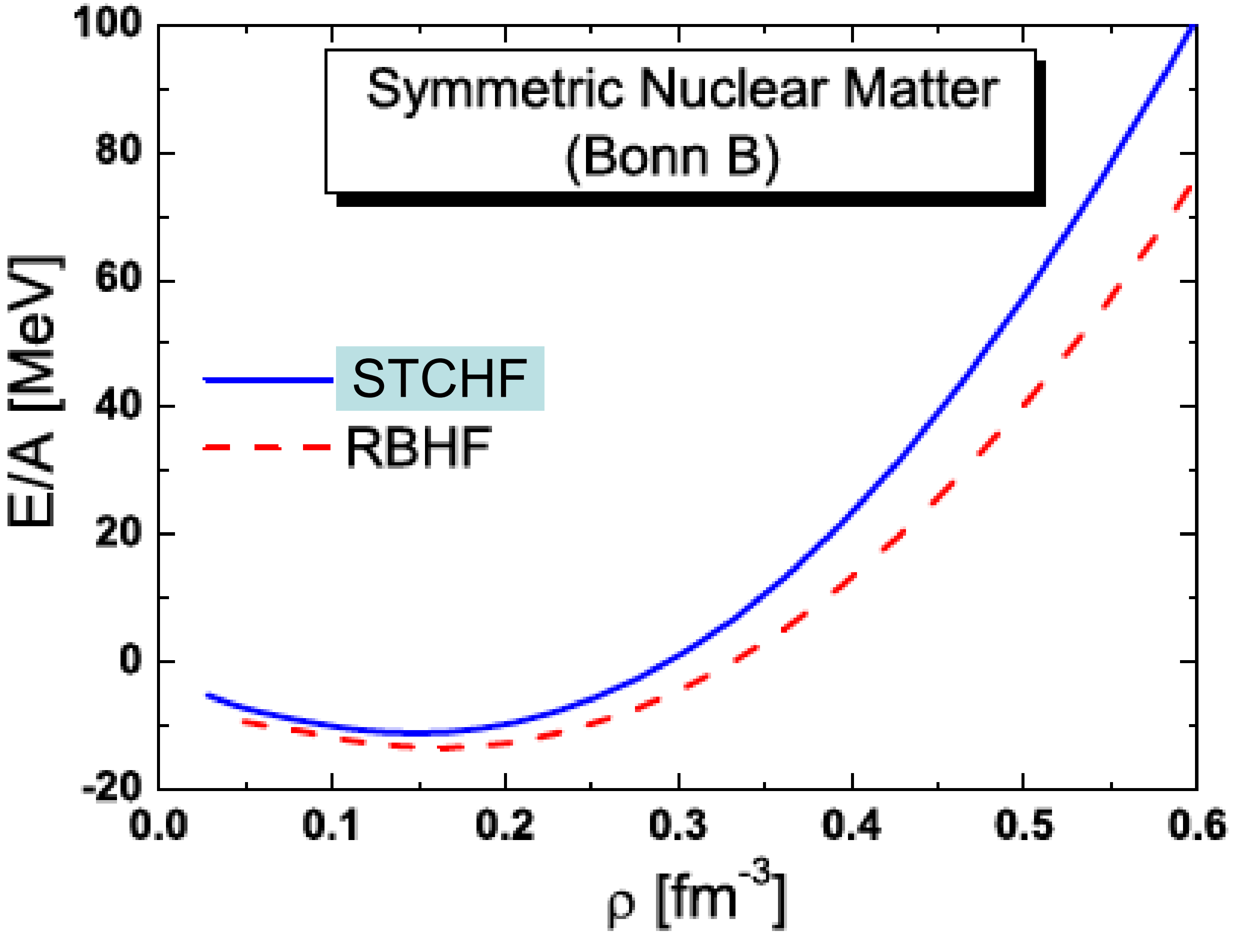
$$\langle 0|H_{eff}|0\rangle = |C_0|^2\langle 0|T+V|0\rangle - |C_0|^2\sum_{\alpha\beta}\langle 0|V|\alpha\rangle\langle\alpha|\frac{1}{H-E}|\beta\rangle\langle\beta|V|0\rangle$$

$$\langle\alpha|H-E|\beta\rangle = E_\alpha\delta_{\alpha\beta} + \langle\beta|\tilde{V}|\alpha\rangle + \underline{\langle 0|H|0\rangle\delta_{\alpha\beta} - E\delta_{\alpha\beta}}$$

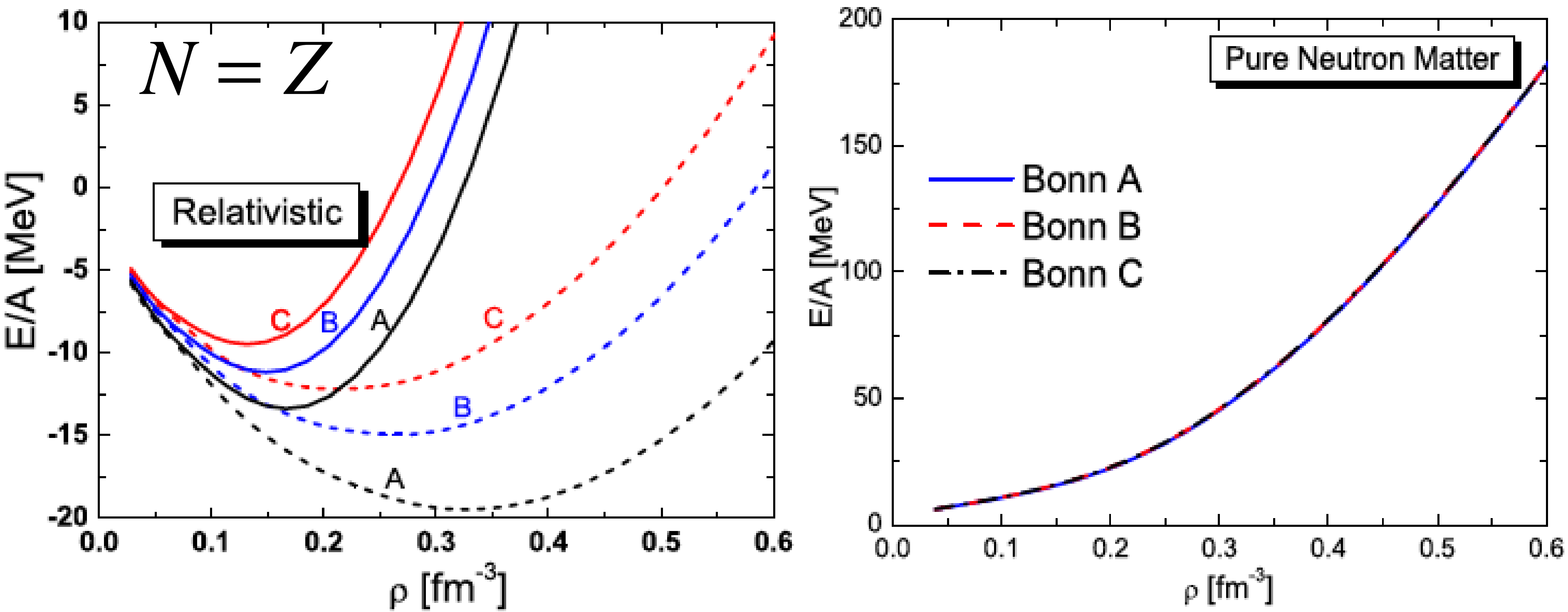


EOS of nuclear matter

Hu Toki Ogawa PTP(2013)

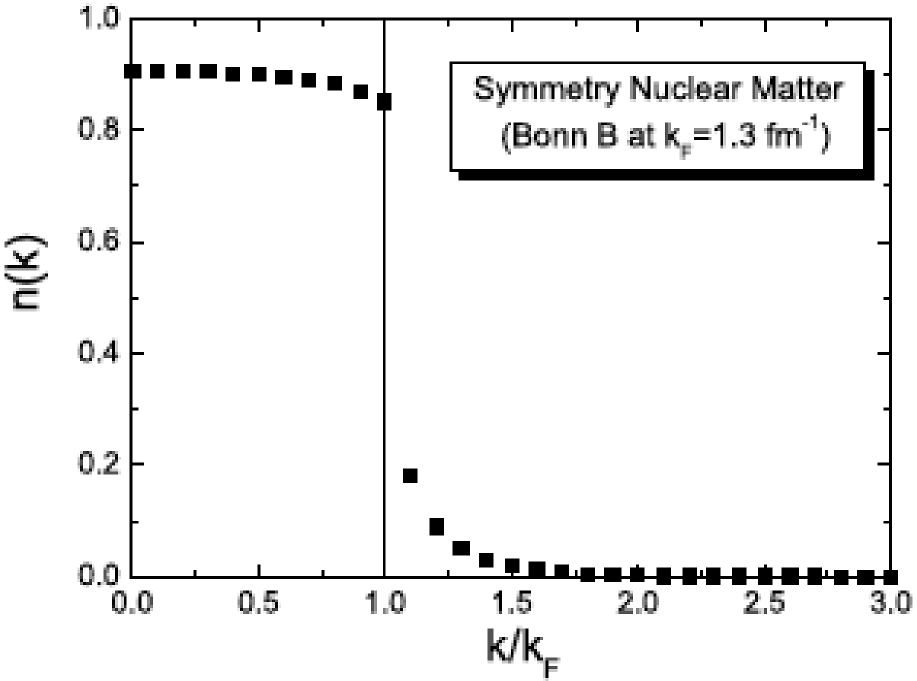


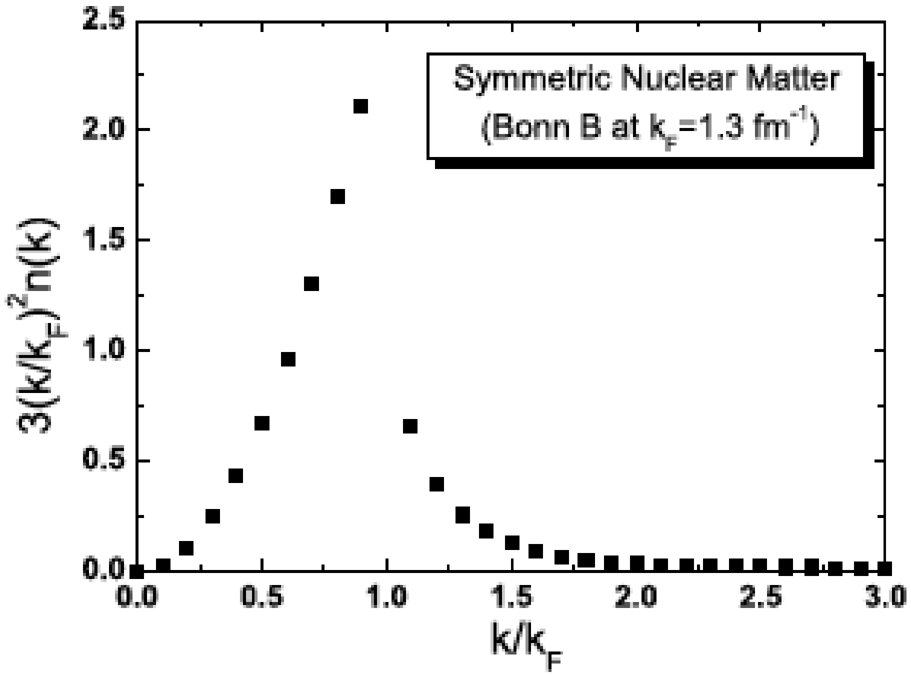
EOS of nuclear matter (N=Z) and (N only)



Relativistic effect provides hard EOS at high density
Tensor effect is small in neutron matter

Momentum distribution



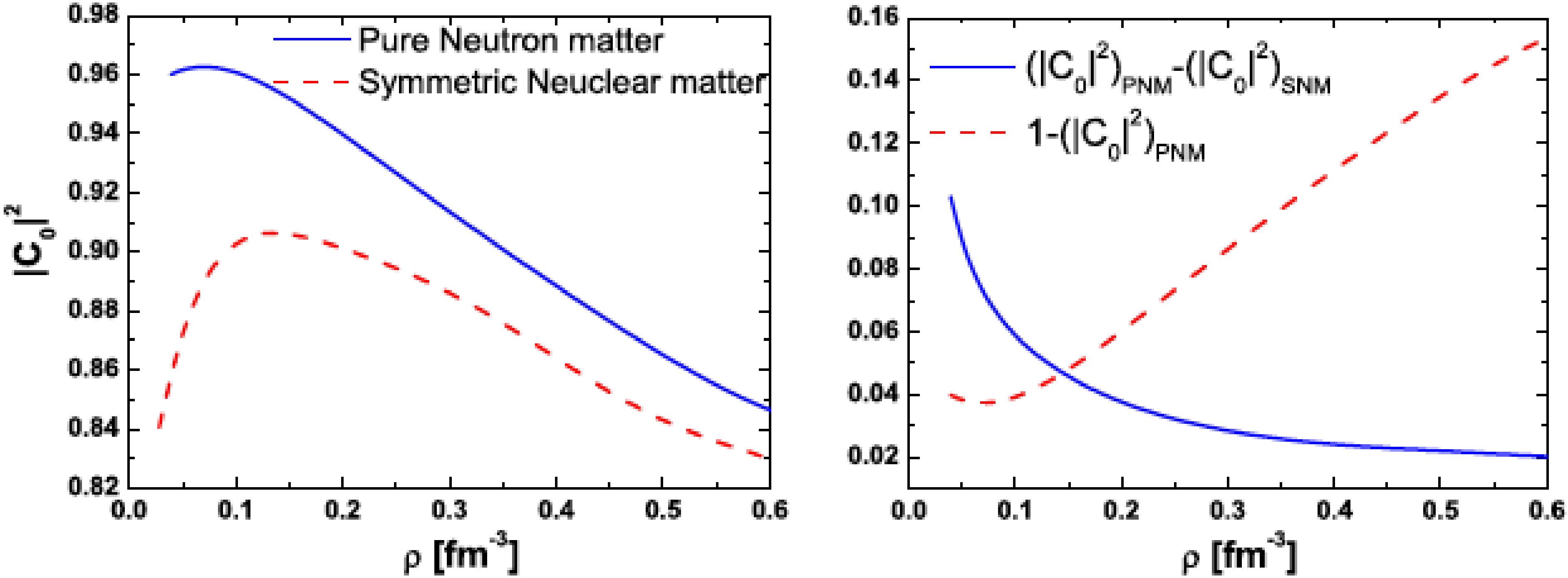


High momentum components

URCA過程

$$n \rightarrow p + e^- + \nu$$

Tensor correlation and Short range correlation

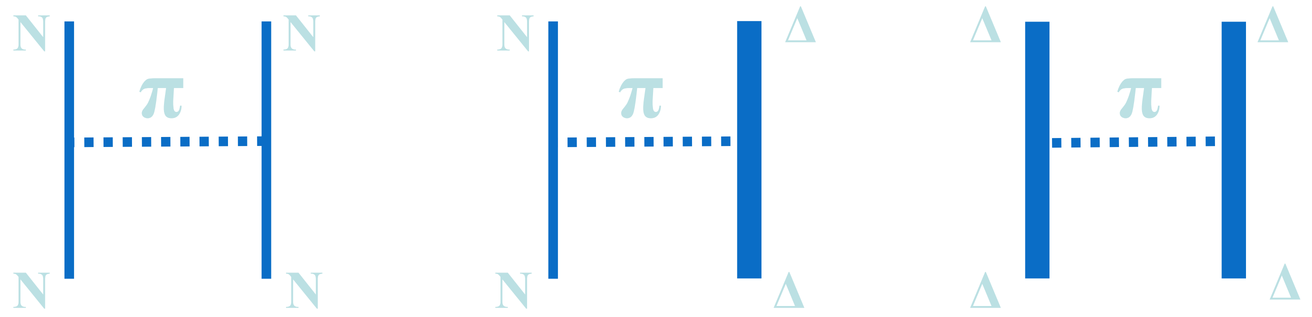


1。Short range correlation increases with density
2。Tensor correlation decreases with density

Treatment of the delta state

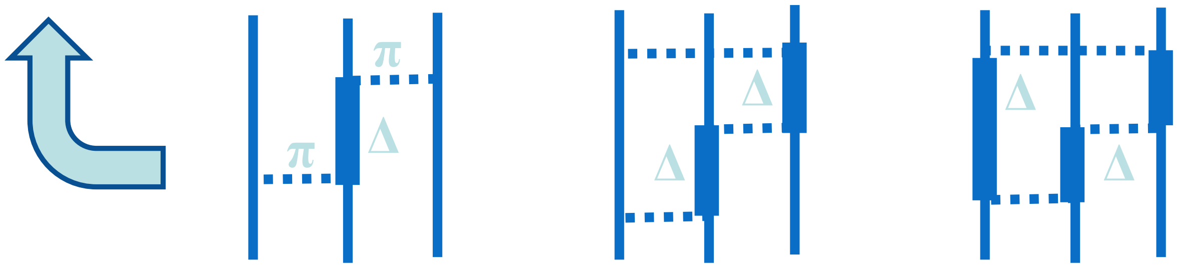
We add the delta degrees of freedom in two-body interaction.

(EX.)



NN channel NΔ channel ΔΔ channel

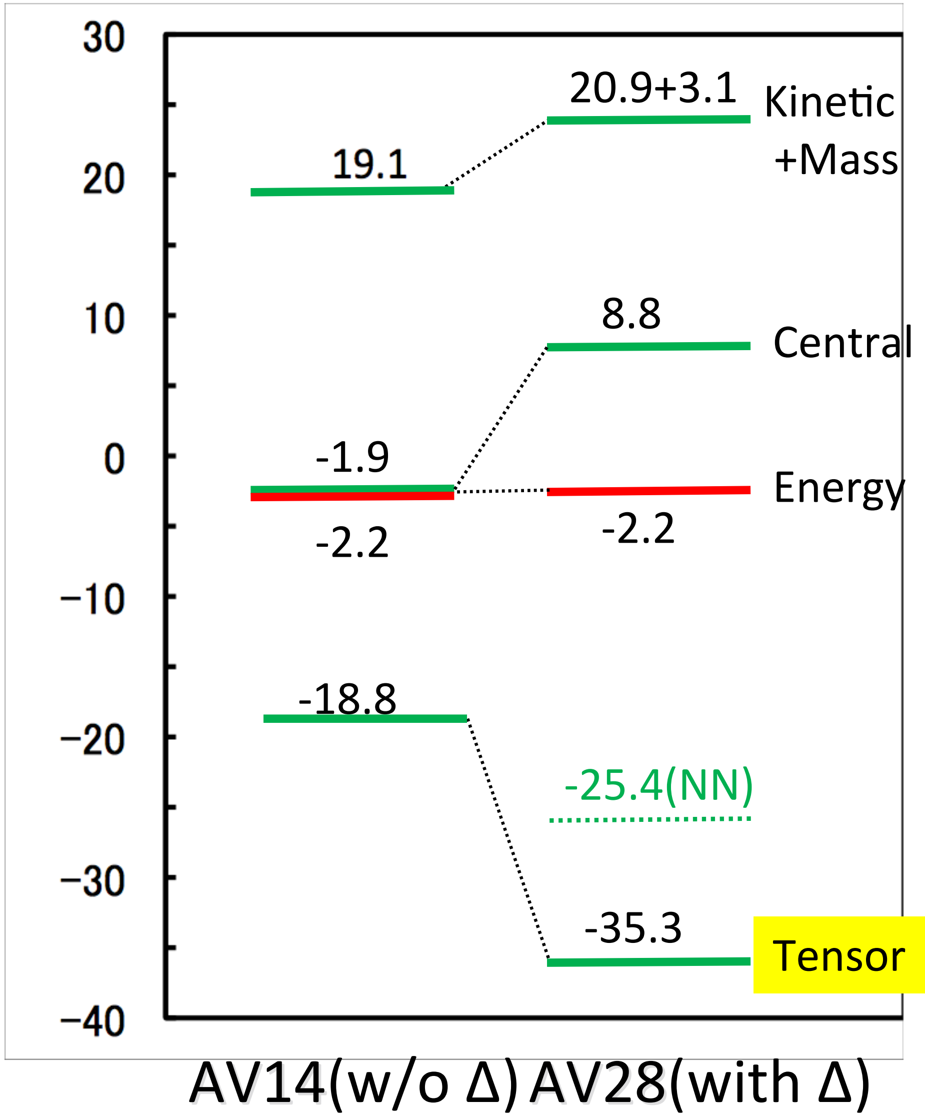
Many-body forces can be treated by the two-body correlations with delta.



Two-body NN interaction with delta degrees of freedom → AV28 potential

We study the three-body system with delta degrees of freedom.
Effect of three-body force? Difference from the NNN three-body system?
We develop the treatment of delta for the framework of TOSM,TOFM,EBFH.

Effect of Δ in deuteron

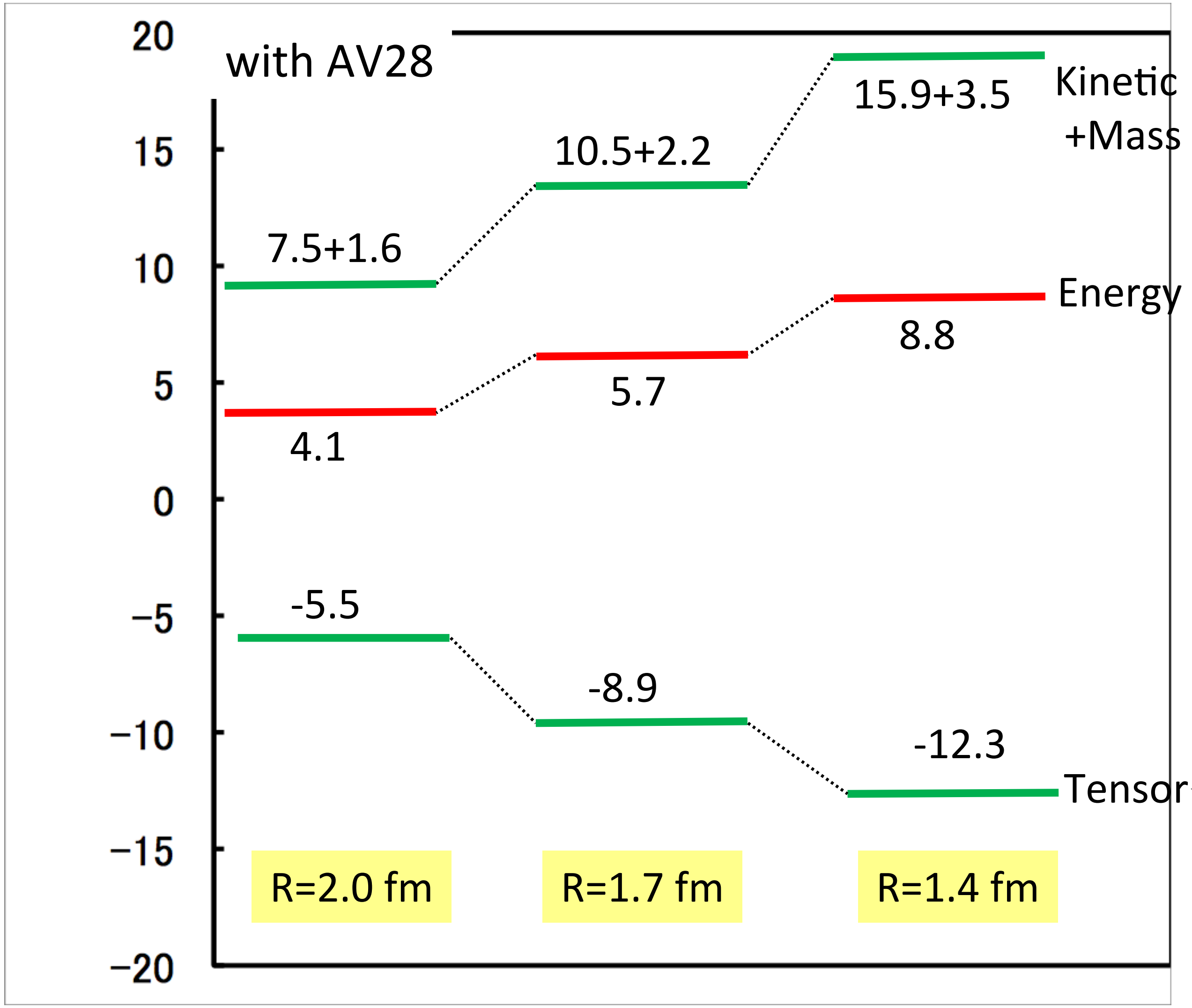


Deuteron 1^+	AV14	AV28
L・S	0.4	0.8
L^2	3.1	3.6
$(L\cdot S)^2$	- 4.0	- 4.1
P_{NN} $[^3S_1]$ %	93.9	93.3
P_{NN} $[^3D_1]$	6.1	6.2
$P_{\Delta\Delta}$ $[^3S_1]$		0.04
$P_{\Delta\Delta}$ $[^3D_1]$		0.02
$P_{\Delta\Delta}$ $[^7D_1]$		0.42
$P_{\Delta\Delta}$ $[^7G_1]$		0.04

$$\Psi_{NN} = |^3S_1\rangle + |^3D_1\rangle$$

$$\Psi_{\Delta\Delta} = |^3S_1\rangle + |^3D_1\rangle + |^7D_1\rangle + |^7G_1\rangle$$

Effect of Δ in ¹E channel (T=1)



Wave function

$$\Psi_{NN} = |{}^1S_0\rangle$$
$$\Psi_{\Delta\Delta} = |{}^1S_0\rangle + |{}^5D_0\rangle$$
$$\Psi_{N\Delta} = |{}^5D_0\rangle$$

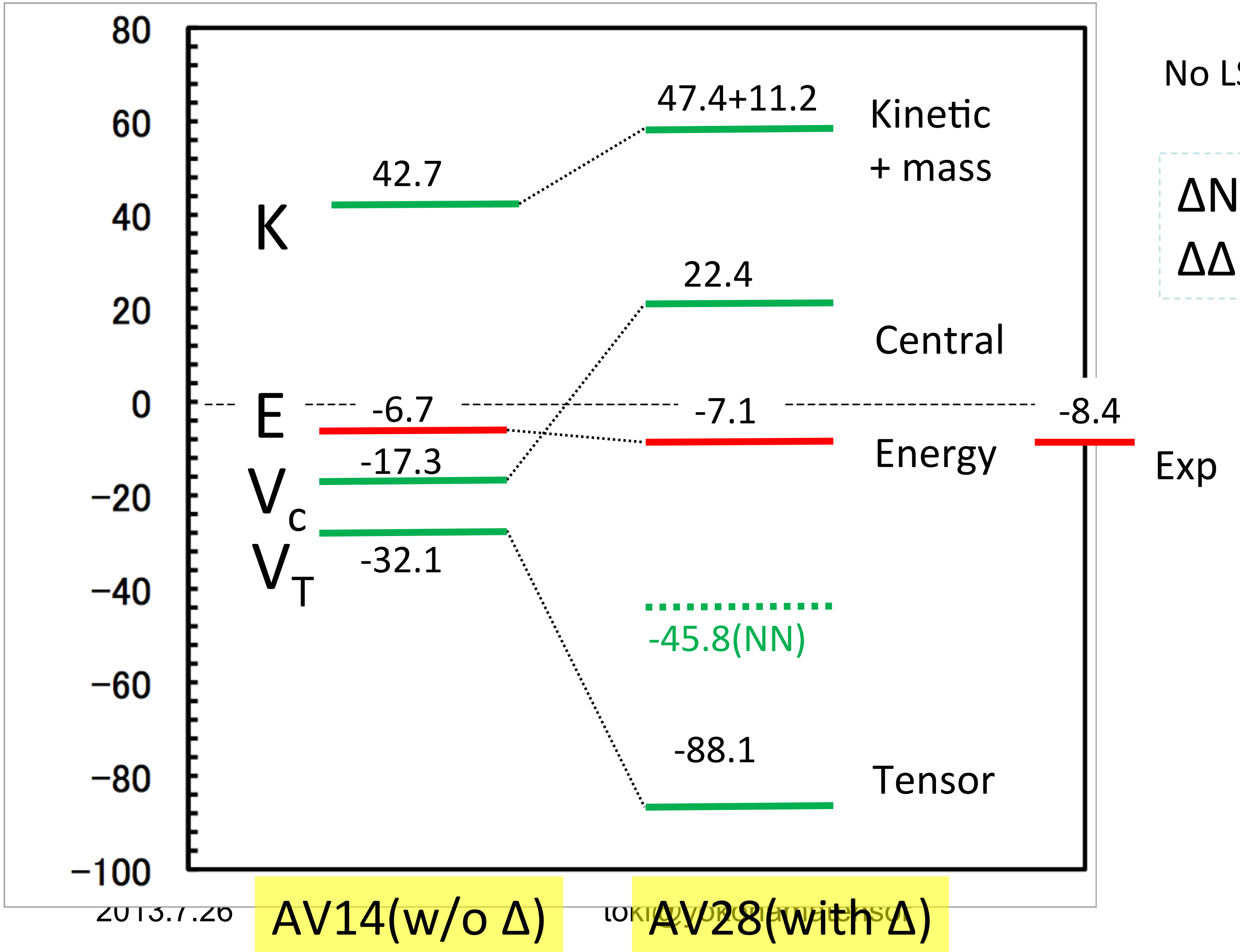
Hamiltonian
with radius constraint

$$\widetilde{H} = H + \lambda \hat{R}^2$$

$\langle S(NN)|V_T|D(N\Delta)\rangle$
$\langle S(NN)|V_T|D(\Delta\Delta)\rangle$

Result ^3H with AV14 & AV28

^3H $J^\pi = 1/2^+$



No LS, L^2,LS^2 forces

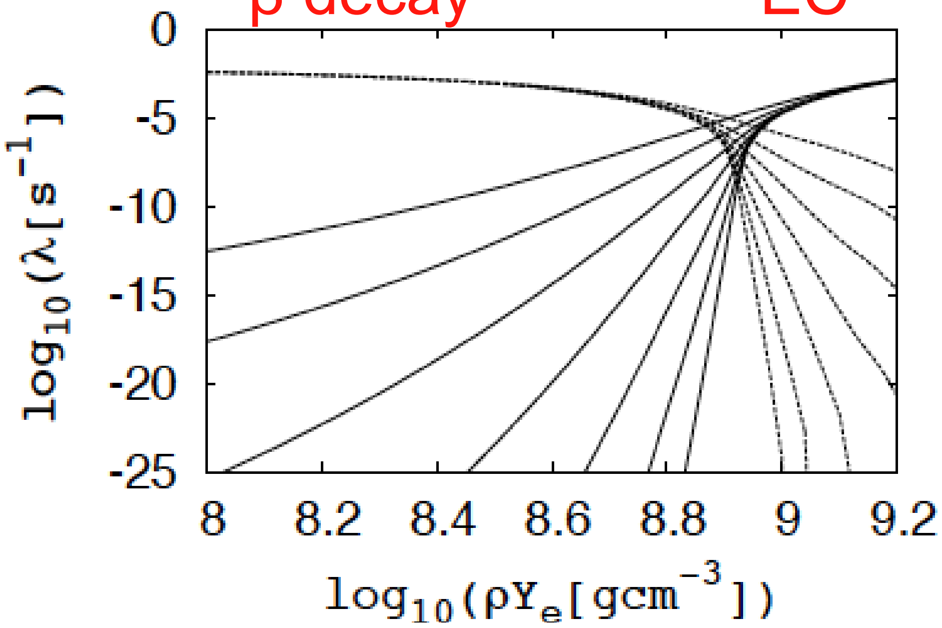
ΔNN 1.5 [%]
ΔΔN 1.1 [%]

Nuclear URCA process for Intermediate Mass Stars

Detailed beta transition rates for URCA nuclear pairs in 8-10 solar mass stars

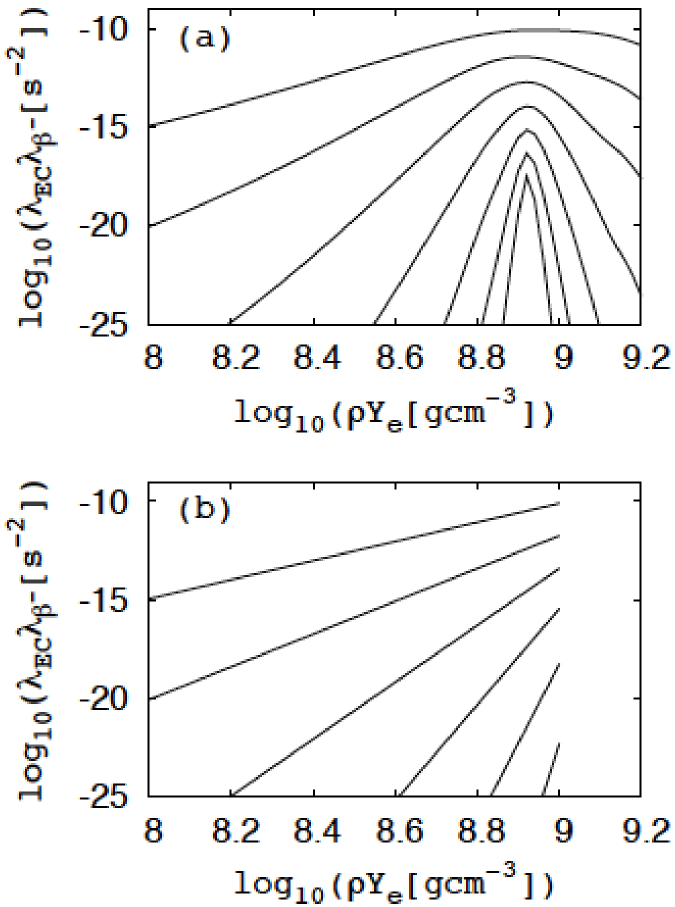
Hiroshi Toki *,[1] Toshio Suzuki †,[2] Ken'ichi Nomoto ‡,[3] Samuel Jones,[4] and Raphael Hirschi[4,3]

Phys. Rev. C 88, 015806 (2013)



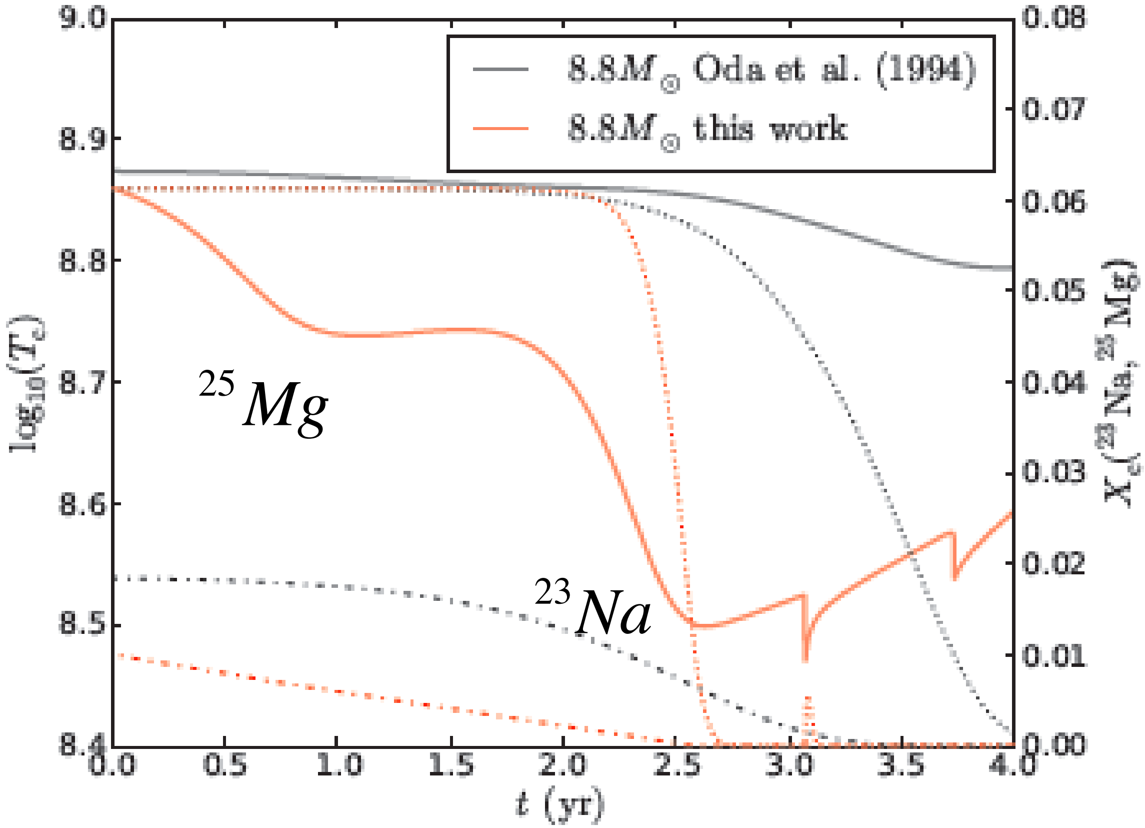
$A = 23: \; ^{23}\mathrm{Na} + e^- \rightarrow \; ^{23}\mathrm{Ne} + \nu$
and $^{23}\mathrm{Ne} \rightarrow \; ^{23}\mathrm{Na} + e^- + \bar{\nu}$

$A = 25: \; ^{25}\mathrm{Mg} + e^- \rightarrow \; ^{25}\mathrm{Na} + \nu$
and $^{25}\mathrm{Na} \rightarrow \; ^{25}\mathrm{Mg} + e^- + \bar{\nu}$



hamate

Stellar evolution of $M=8.8M_o$



$0\sim0.5M_o$ He white dwarf
$0.5\sim8M_o$ C-O white dwarf
$8\sim10M_o$??? O-Ne-Mg core collapse
$>10_o$ Fe core collapse

Nuclear Physics with tensor interaction

- We have developed STCHF theory to treat pion
- STCHF theory provides foundation of BHF theory
- Tensor interaction provides the saturation mechanism
- Delta provides three body interaction
- Nuclear URCA process (more supernova)