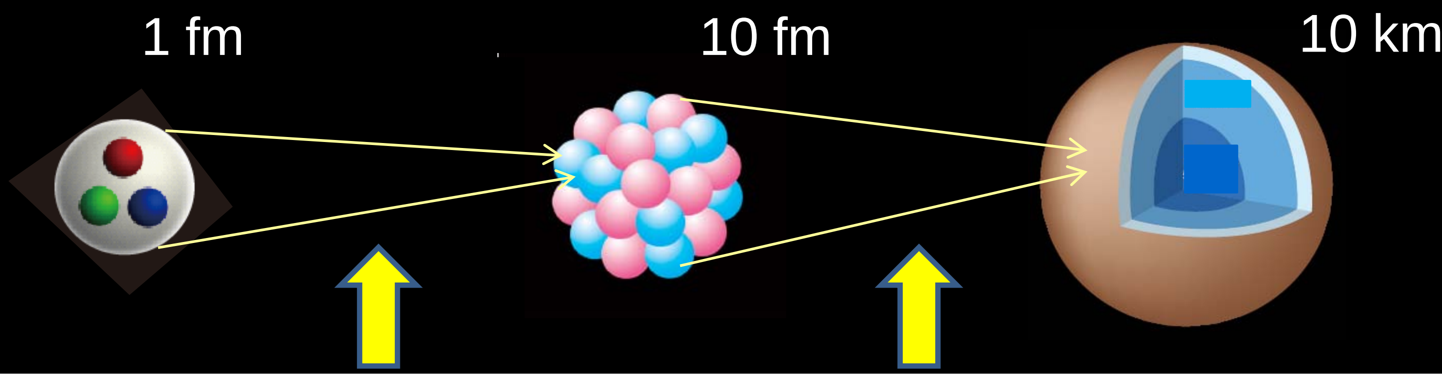
Research Group A02 Report (2008-2012)

Nuclear Physics Project



1.Hadron int. from LQCD
S. Aoki (Tsukuba)
K. Sasaki (Tsukuba)
N. Ishii (Tsukuba)
H. Nemura (Tsukuba)

2. Ab initio Few-Body Cal.
E. Hiyama (RIKEN)
K. Murano (RIKEN)

4. Time dep. DFT
T. Nakatsukasa (RIKEN)
K. Sato (RIKEN)
K. Yabana (Tsukuba)

1.Hadron int. from LQCD
T. Hatsuda (RIKEN)
S. Ozaki (Tokyo)
Y. Ikeda (Tokyo/RIKEN)
S. Sasaki (Tokyo)

3. Ab initio Many-Body Cal.
T. Otsuka (Tokyo)
T. Abe (Tokyo)
N. Shimizu (Tokyo)
S. Fujii (Tokyo)
T. Suzuki (Nihon)

5. Dense matter
A. Nakamura (Hiroshima)
K. Nagata (Hiroshima)
M. Takano (Waseda)

→ HPCI Field5 Subjects 1,2 (2011-2015)

Summary of A02 achievements

PTEP
Progress of Theoretical and Experimental Physics

Progress of Theoretical and Experimental Physics, (2012) special volume
"Computational Approaches in Particle, Nuclear and Astrophysics"
http://www.oxfordjournals.org/our_journals/ptep/special_issue_a.html

1. **Lattice quantum chromodynamical approach to nuclear physics**
   HAL QCD Collaboration, *Prog. Theor. Exp. Phys.* (2012) 01A105.

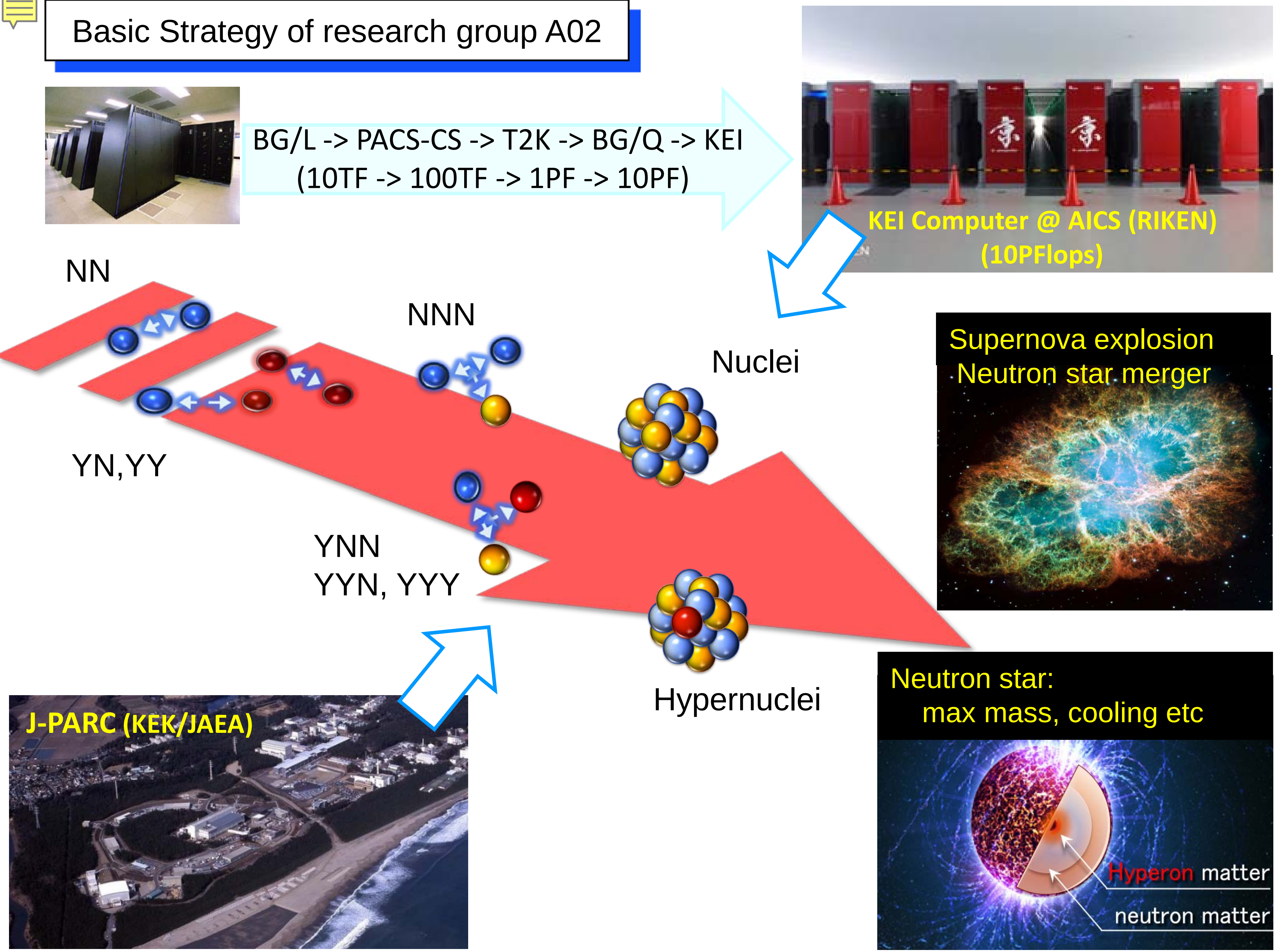
2. **Gaussian expansion method for few-body systems and its applications to atomic and nuclear physics**
   E. Hiyama, *Prog. Theor. Exp. Phys.* (2012) 01A204

3. **New-generation Monte Carlo shell model for the K computer era**
   N. Shimizu et al., *Prog. Theor. Exp. Phys.* (2012) 01A205

4. **Density functional approaches to collective phenomena in nuclei: Time-dependent density functional theory for perturbative and non-perturbative nuclear dynamics**
   T. Nakatsukasa, *Prog. Theor. Exp. Phys.* (2012) 01A207.

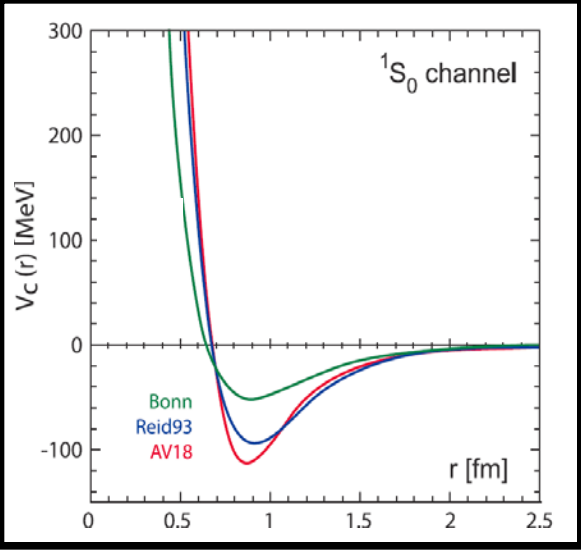
5. **Towards extremely dense matter on the lattice**
   XQCD-J Collaboration, *Prog. Theor. Exp. Phys.* (2012) 01A103.

Basic Strategy of research group A02

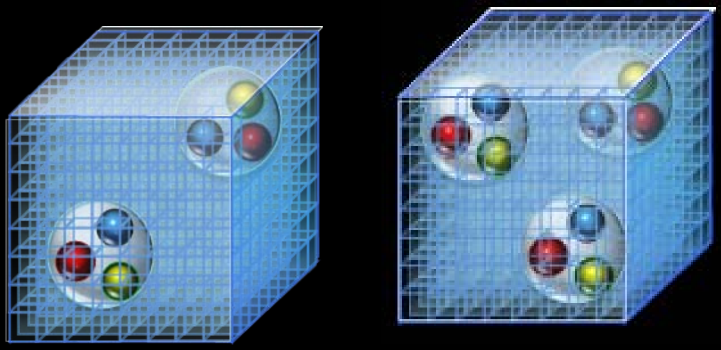


BB & BBB force from lattice QCD

“high precision” NN interactions	# of parameters
CD Bonn	38
AV18	40
EFT in N^3LO	24



QCD has only four parameters :
m_u, m_d, m_s, Λ_{QCD}

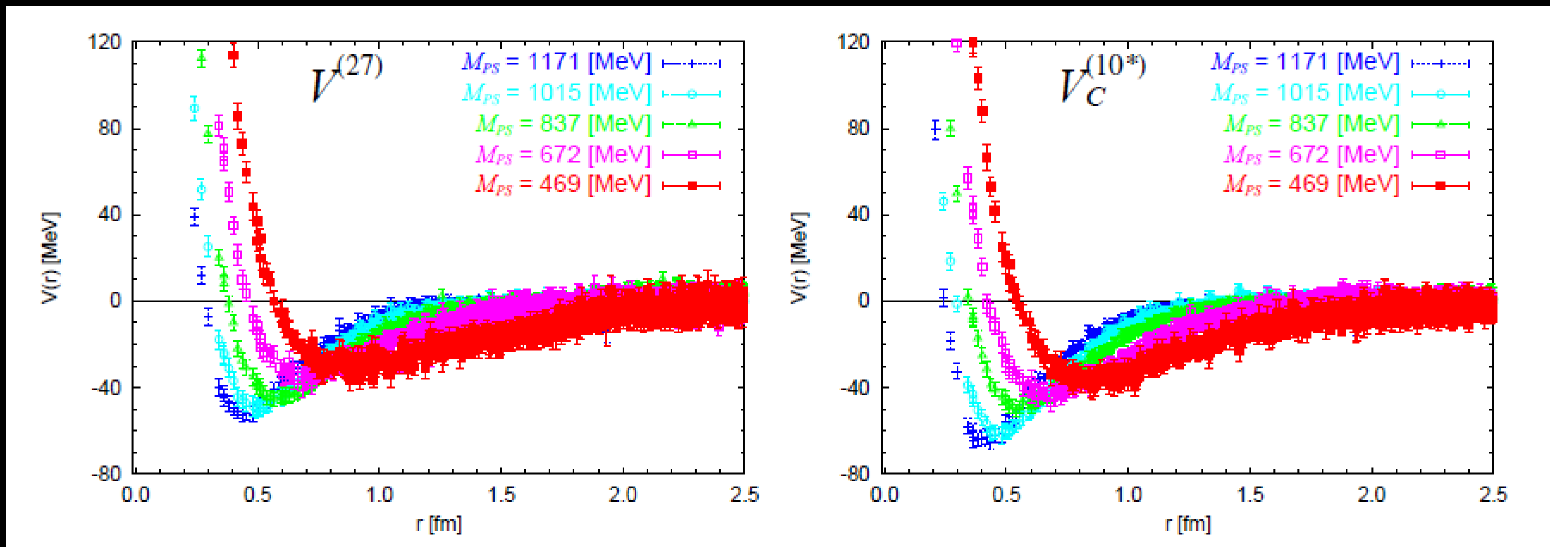


HAL QCD method for hadron-hadron interactions

BB potentials (flavor SU(3) limit)

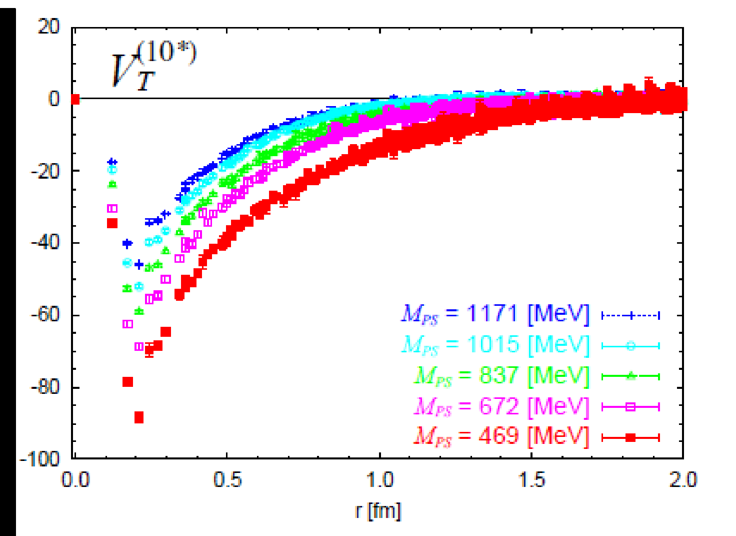
IHAL QCD Coll.
Phys. Rev. Lett. 106 (2011) 162002
Nucl. Phys. A881 (2012) 28

Repulsive core in NN channel



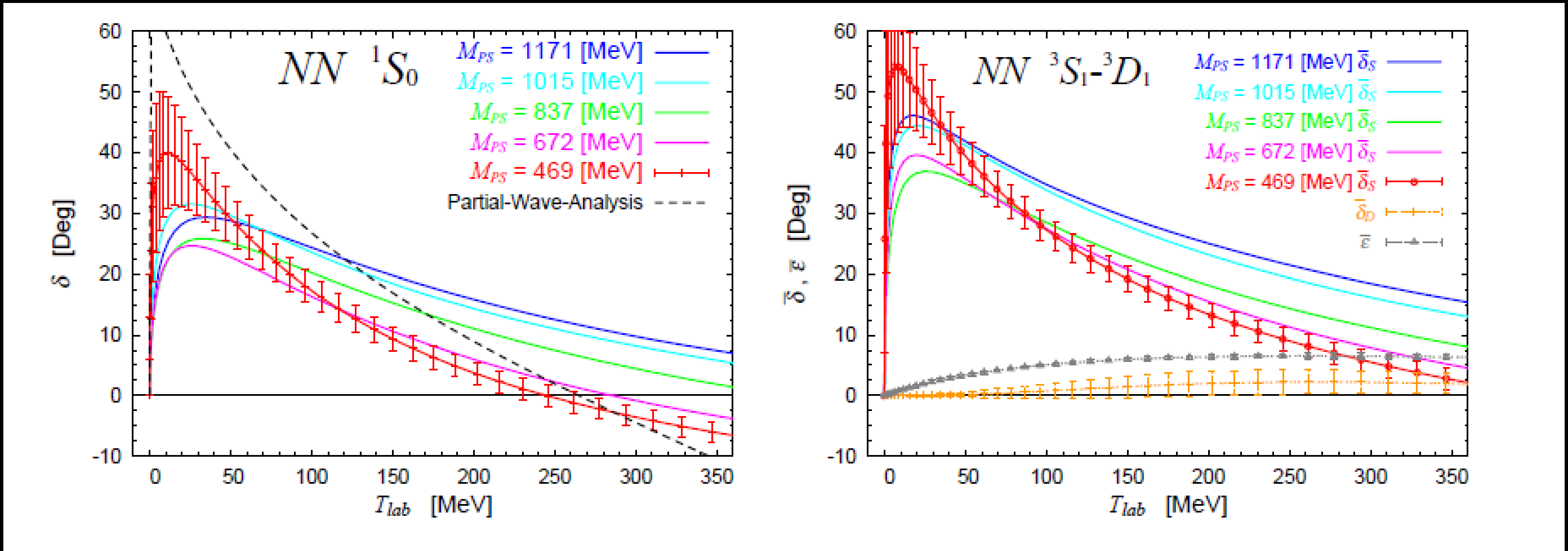
$^1S_0$ channel

$^3S_1 - {}^3D_1$ channel



Growing NN tensor force

NN phase shifts (flavor SU(3) limit)



Attraction stonger in the deuteron channel

HAL QCD Coll.,
Phys. Rev. Lett. 106 (2011) 162002
Nucl. Phys. A881 (2012) 28

Highlights (2008-2012) in Lattice Nuclear Force

- basic concepts of the NN ineracition in LQCD

  S. Aoki, T. Hatsuda & N. Ishii, PTP 123 (2010) 89

  N. Ishii et al. [HAL QCD Coll.], Phys.Lett. B712 (2012) 437

- central, tensor, LS forces → Doi (Fri.), Ishii, Murano (poster)

- SU(3) BB force, H-dibaryon & $N_{☆}$ → Inoue (Fri.)

  T. Inoue et al. [HAL QCD Coll.], PRL 106 (2011) 162002

  T. Inoue et al. [HAL QCD Coll.], Nucl.Phys. A881 (2012) 28

- YN and YY forces → K. Sasaki, Yamada, Nemura (poster)

  H. Nemura et al. [HAL QCD Coll.], Phys.Lett. B673 (2009) 136

- NNN force and unified contraction algorithm → T. Doi (Fri.)

  T. Doi et al. [HAL QCD Coll.], PTP 127 (2012) 723

- meson-baryon interactions → Charron, Ikeda, Ozaki (poster)

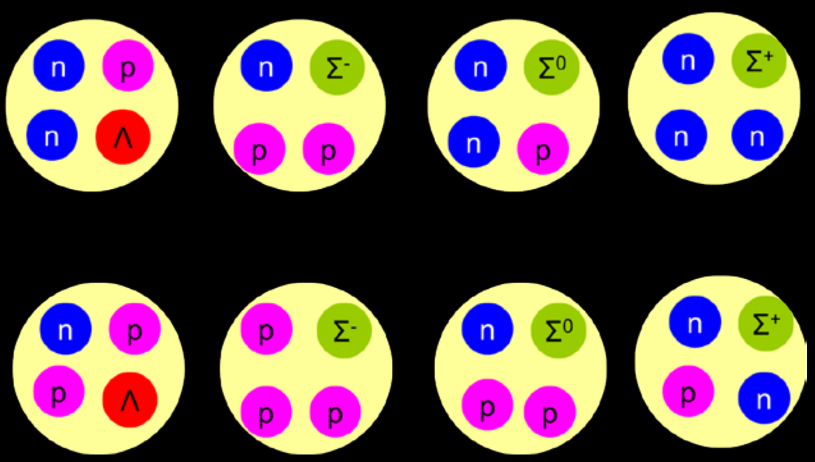
  T. Kawani and S. Sasaki, Phys. Rev. D82 (2010) 091501

→ LQCD: 96^4 lattice, a=0.1fm, L=9.6fm, m_π=135MeV at K cmputer

Ab initio nuclear few-body calculations

Gaussian Expansion Method (GEM)
for N-body problems (N=3,4,5,…) by E. Hiyama

- nuclei
- hypernuclei
- cold atoms



Summary of progress（FY 2008-2012）

i) Applying Gaussian Expansion Method to N-body problems

→ N=5 became possible by now

ii) Establishing the following frameworks

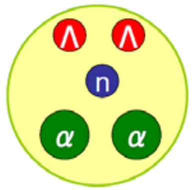
- any interactions such as
  central force, spin-orbit force, tensor force,
  momentum dependent force, quadratic spin-orbit force etc.

- particle conversion interactions such as
  ΛN−ΣN, ΛΛ−ΞN−ΣΣ etc.

- bound states, resonant states and continuum states,
  simultaneously

Observation of Hida event

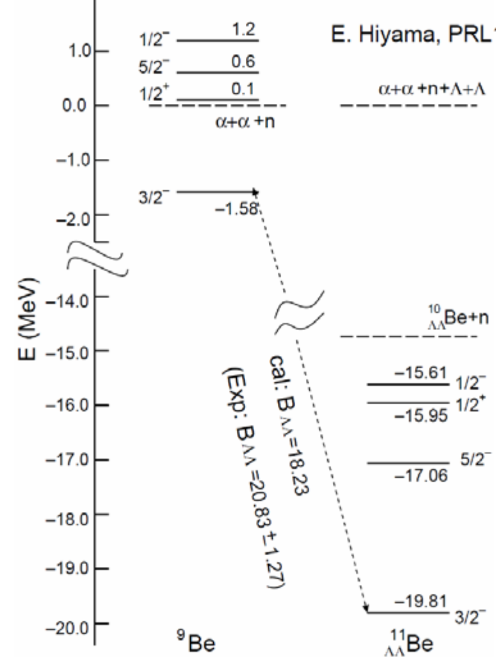
KEK-E373 experim



$^{11}_{\Lambda\Lambda}$Be

$B_{\Lambda\Lambda}$ = 20.49±1.15 MeV

Important issue:
Is the Hida event the observation of a ground state or an excited state?

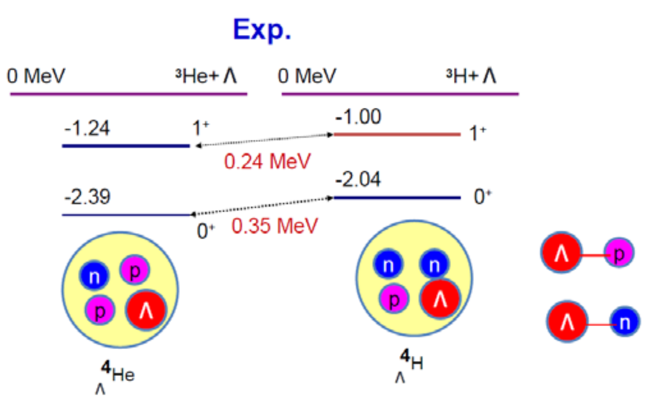


E. Hiyama, PRL104, 212502(2010)

We succeeded in interpreting this event as an observation of the ground state of $^{11}_{\Lambda\Lambda}$Be.

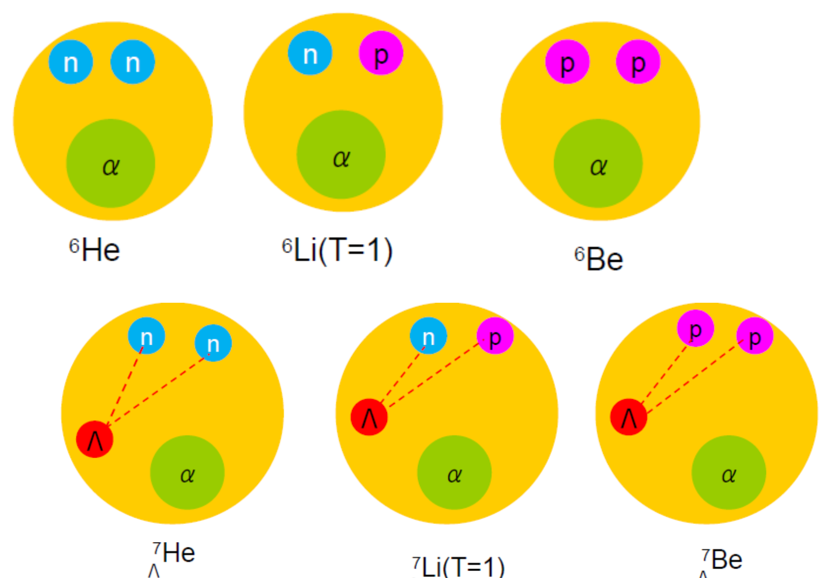
Also, we succeeded in performing 5-body problem.

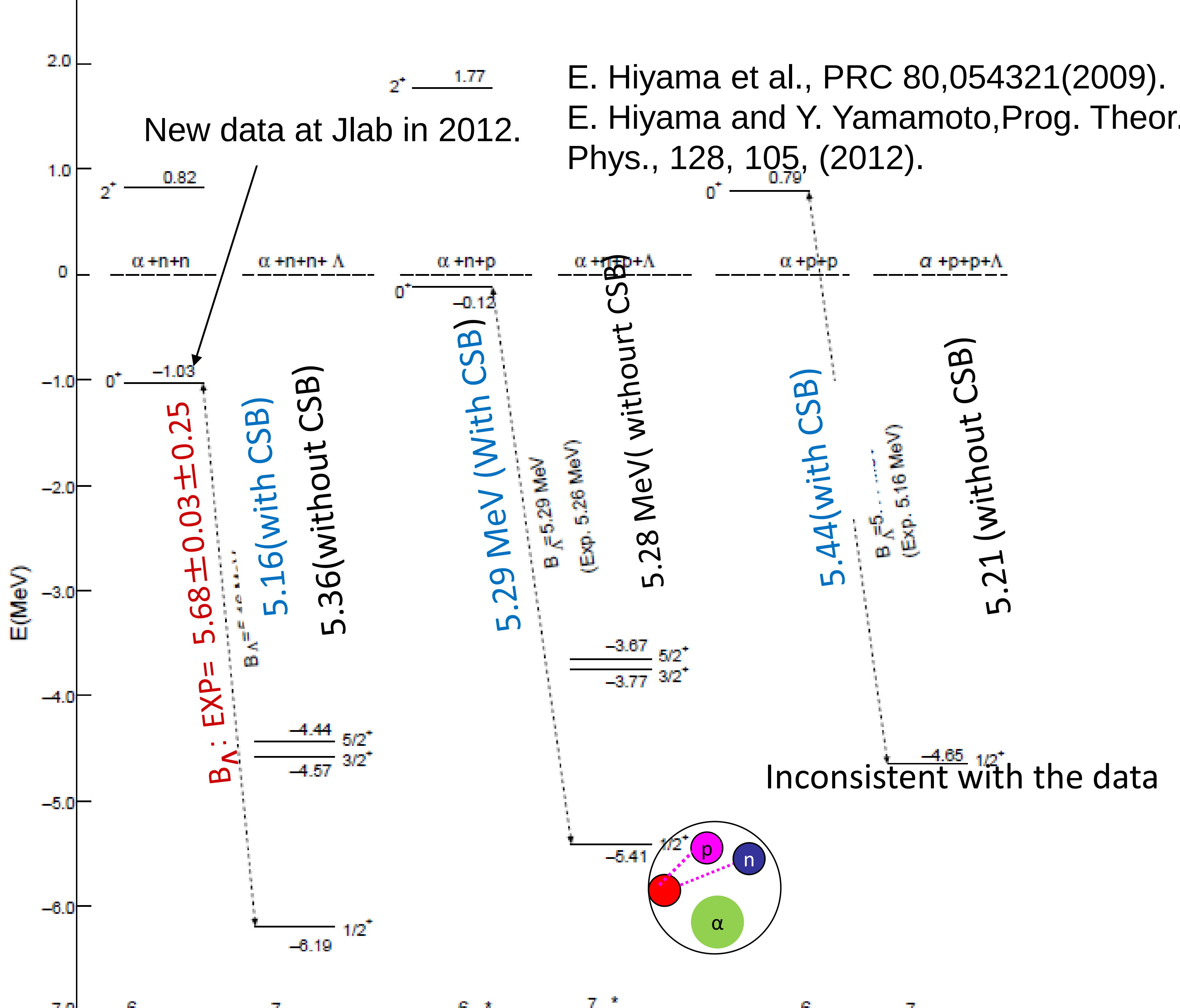
Charge Symmetry breaking



For this purpose, it is interesting to investigate the CSB effect in p-shell Λ hypernuclei as well as s-shell Λ hypernuclei.

For this purpose, to study structure of A=7 Λ hypernuclei is suited. Because, core nuclei with A=6 are iso-triplet states.



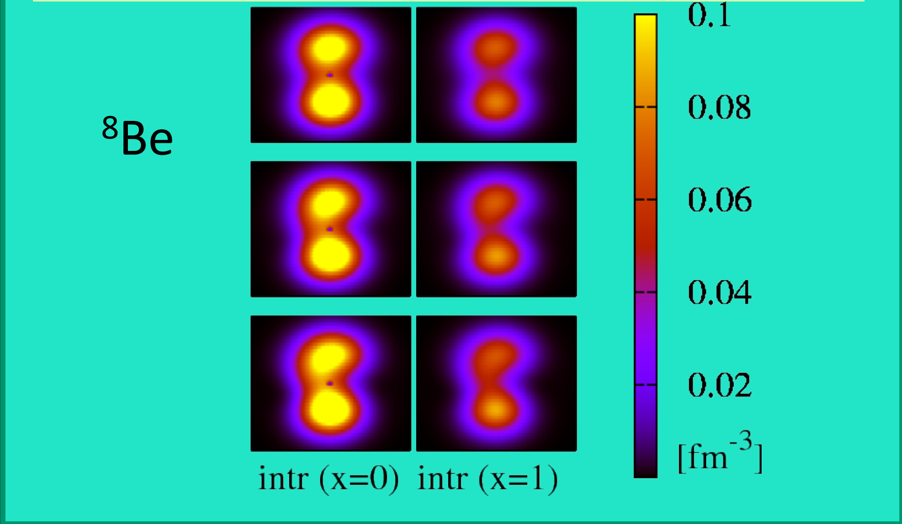

E. Hiyama et al., PRC 80,054321(2009).
E. Hiyama and Y. Yamamoto,Prog. Theor. Phys., 128, 105, (2012).
New data at Jlab in 2012.
E(MeV)
2.0
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
2+ 0.82
0+ −1.03
α +n+n
α +n+n+ Λ
−4.44 5/2+
−4.57 3/2+
1/2+ −6.19
B_Λ : EXP= 5.68±0.03±0.25
5.16(with CSB)
5.36(without CSB)
2+ 1.77
0+ −0.12
α +n+p
α +n+p+Λ
5.29 MeV (With CSB)
B_Λ=5.29 MeV
(Exp. 5.26 MeV)
5.28 MeV(withourt CSB)
−3.67 5/2+
−3.77 3/2+
1/2+ −5.41
p
n
α
0+ 0.79
α +p+p
α +p+p+Λ
5.44(with CSB)
(Exp. 5.16 MeV)
5.21 (without CSB)
−4.65 1/2+
Inconsistent with the data

Ab initio nuclear many-body calculations

Monte Carlo Shell Model (MCSM) by T. Otsuka et al.

- a tool to go beyond the Lanczos method
- variational wave function + energy-variance extrapolation
- obtain a few lowest eigenstates
- small I/O, good parallel

Intrinsic Density from ab initio calc.



Summary of progress（FY 2008-2012）

N.B. SPIRE Field 5 launched since FY2011

- Monte Carlo Shell Model
  - ***Methodology developments*** :

    Algorithm development (8 times accelerated)

    Y. Utsuno *et al.*, Comp. Phys. Comm. **184** 102 (2013).

    Energy-variance extrapolation for precise estimation of eigenenergies

    N. Shimizu *et al.*, Phys. Rev. C **82** 061305R (2010), ibid **85** 054301(2012).
  - ***Applications*** :

    No-core calculations in light-mass nuclei ⇨ Abe (Fri.)

    T. Abe *et al.*, Phys. Rev. C **86** 054301 (2012),

    L. Liu *et al.*, Phys. Rev. C **86** 014302 (2012)

    Shell-model calc. in medium-heavy nuclei ⇨ Tsunoda (Fri.)

    Neutron-rich Ni, Cr isotopes and shell evolution (Y. Tsunoda *et al.*),

    Xe, Ba isotopes and shape "phase" transition (N. Shimizu *et al.*)

✓ For review: N. Shimizu, *et al.* Prog. Theor. Exp. Phys. **2012** 01A205 (2012).

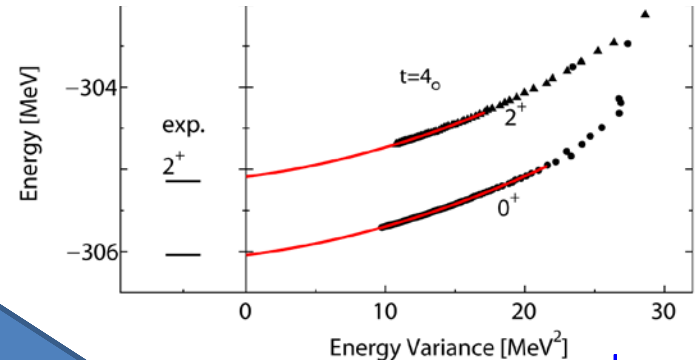
Developments of the Monte Carlo shell Model towards "K computer"

T. Otsuka, M. Honma, T. Mizusaki, N. Shimizu, and Y. Utsuno, Prog. Part. Nucl. Phys. **47**, 319 (2001).

PC cluster
100CPU parallel

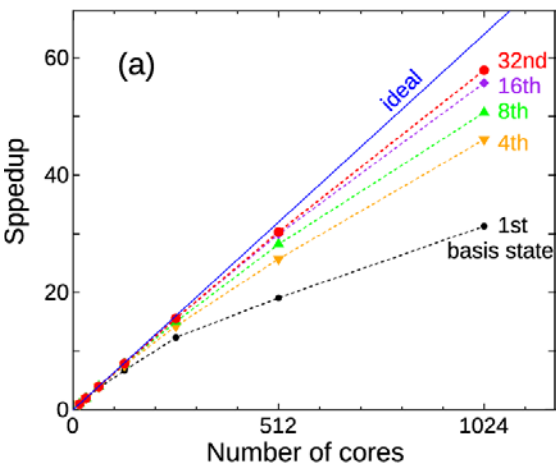
N. Shimizu, Y. Utsuno, T. Mizusaki, T. Otsuka, T. Abe, and M. Honma, Phys. Rev. C **82,** 061305(R) (2010).

- Precise estimation of energy eigenvalue by variance extrapolation + reordering technique



N. Shimizu et al., Phys. Rev. C 85 054301(2012).

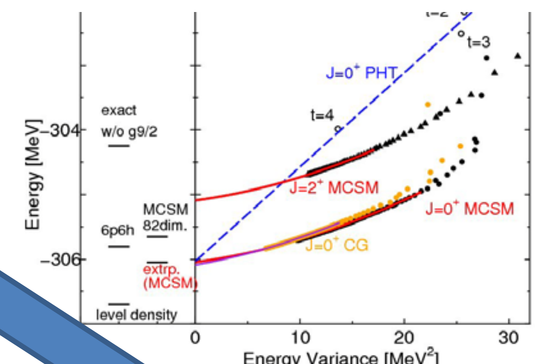
Parallel efficiency



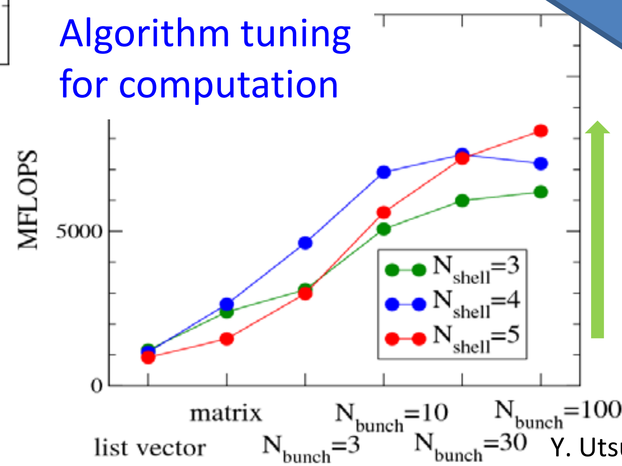
OpenMP+MPI hybrid parallel

N. Shimizu, *et al.* Prog. Theor. Exp. Phys. **2012** 01A205 (2012).

Improvement of the MCSM by Conjugate Gradient method



Algorithm tuning for computation



8 times faster at maximum

Y. Utsuno, N. Shimizu, T. Otsuka, and T. Abe, Comp. Phys. Comm. 184 102 (2013).

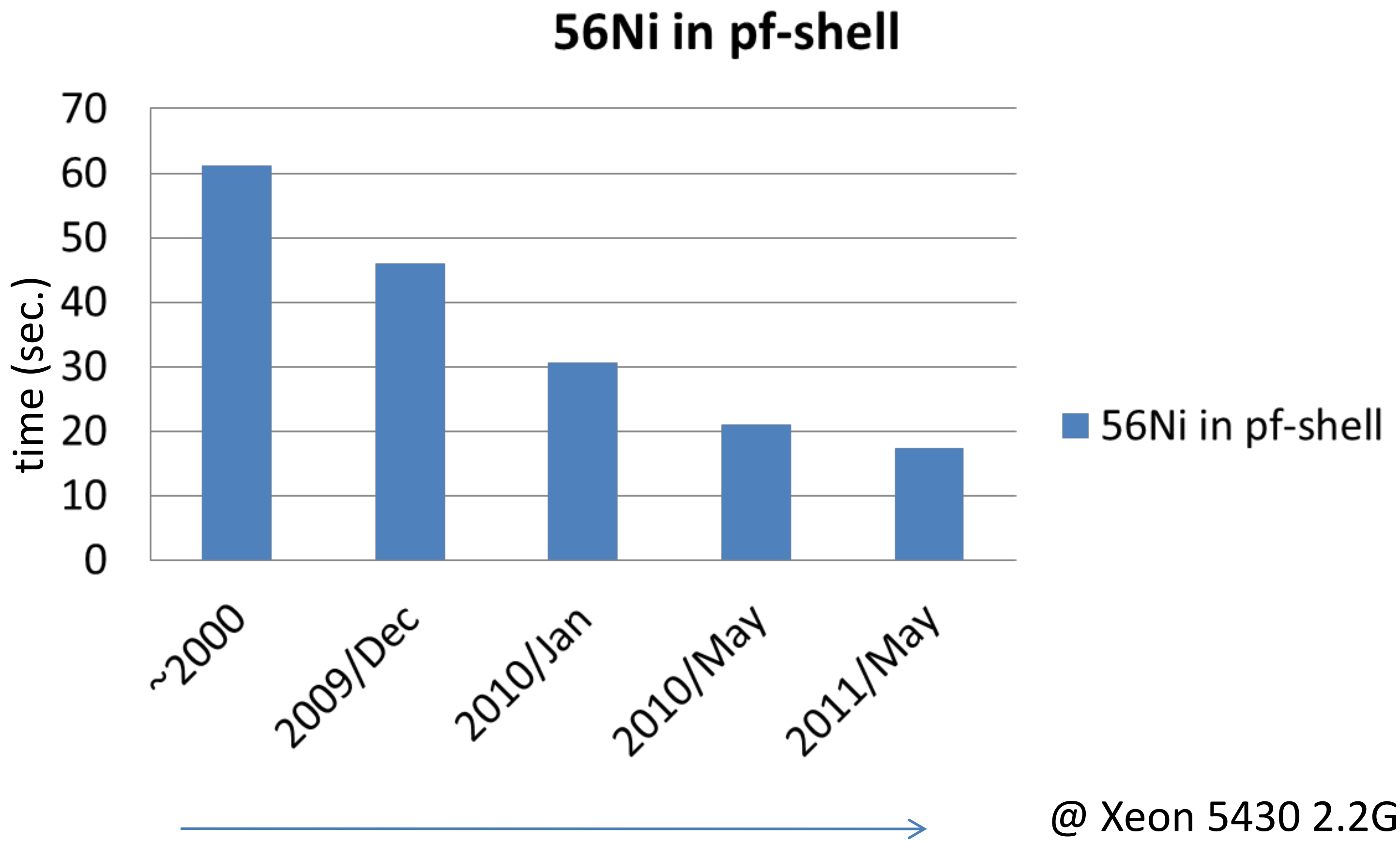
100 CPUs

Towards 10^5 cores

SPARC64 VIIIfx 705,024 cores

K computer

Performance improvement of the MCSM code in a single processor



@ Xeon 5430 2.2GHz

3.5 times speed up
10 times speed up for no-core shell model calc.

The performance improvement owes to the rewritten algorithm.

Time Dependent Density Functional Theory

Time-dependent Kohn-Sham-Bogoliubov (TDKSB) eq.
by Nakatsukasa and Yabana

$$i\frac{\partial}{\partial t}\Psi(t) = \mathcal{H}_s(t)\Psi(t) - \Psi(t)\Xi(t),$$

$$\beta$$

$$\gamma \quad \Delta_n \quad \Delta_p$$

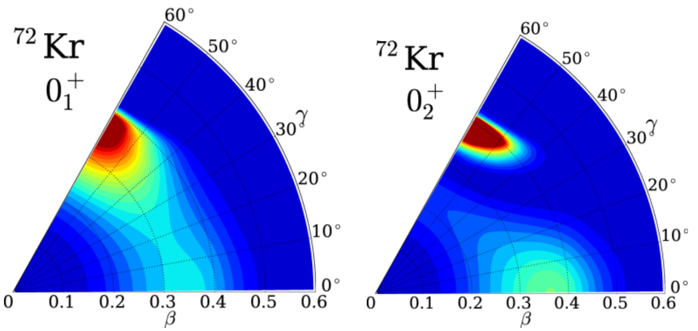
$$-\lambda_n \quad -\lambda_p$$

Nuclear dynamics in the density functional theory (DFT)

- Developments in new DFT computer codes
  - Static DFT
    - DFT with the iso-rotational invariance (pn mixing)
  - Linear response in TDDFT
    - Real-time approach to E1 response
    - Systematic calculation of photonuclear reactions with the finite amplitude method
  - Beyond the linear regime
    - Shape fluctuation and shape transition with a microscopically-derived collective Hamiltonian
    - Real-time description of fusion dynamics

TDDFT description of microscopic nuclear dynamics

Large amplitude shape dynamics

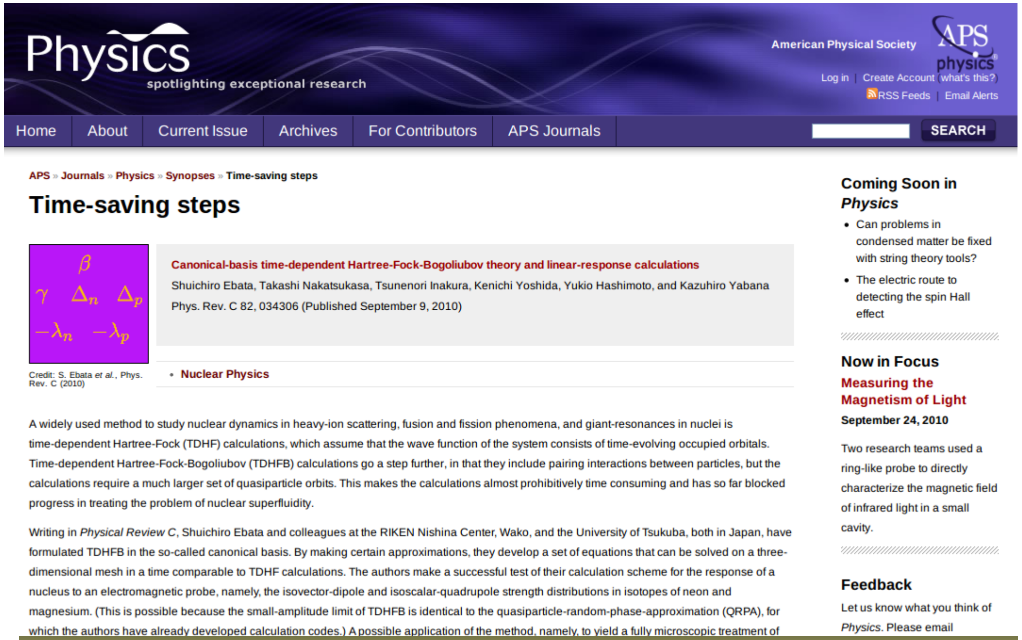


Hinohara et al., PRC **82**, 064313 (2010) ; PPC 84, 061302(R) (2011)

Sato et al, PRC 86, 024316 (2012)

Shape coexistence phenomena are being recognized as a kind of universal feature in nuclei. Quantum shape fluctuation and mixing are described by the quantized collective Hamiltonian obtained through the TDDFT.

Ebata et al., PRC **82**, 034306 (2010); JPCS 312, 092023 (2011)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Time-saving steps

Canonical-basis time-dependent Hartree-Fock-Bogoliubov theory and linear-response calculations

Shuichiro Ebata, Takashi Nakatsukasa, Tsunenori Inakura, Kenichi Yoshida, Yukio Hashimoto, and Kazuhiro Yabana

Phys. Rev. C 82, 034306 (Published September 9, 2010)

Credit: S. Ebata *et al.*, Phys. Rev. C (2010)

• Nuclear Physics

A widely used method to study nuclear dynamics in heavy-ion scattering, fusion and fission phenomena, and giant-resonances in nuclei is time-dependent Hartree-Fock (TDHF) calculations, which assume that the wave function of the system consists of time-evolving occupied orbitals. Time-dependent Hartree-Fock-Bogoliubov (TDHFB) calculations go a step further, in that they include pairing interactions between particles, but the calculations require a much larger set of quasiparticle orbits. This makes the calculations almost prohibitively time consuming and has so far blocked progress in treating the problem of nuclear superfluidity.

Writing in *Physical Review C*, Shuichiro Ebata and colleagues at the RIKEN Nishina Center, Wako, and the University of Tsukuba, both in Japan, have formulated TDHFB in the so-called canonical basis. By making certain approximations, they develop a set of equations that can be solved on a three-dimensional mesh in a time comparable to TDHF calculations. The authors make a successful test of their calculation scheme for the response of a nucleus to an electromagnetic probe, namely, the isovector-dipole and isoscalar-quadrupole strength distributions in isotopes of neon and magnesium. (This is possible because the small-amplitude limit of TDHFB is identical to the quasiparticle-random-phase-approximation (QRPA), for which the authors have already developed calculation codes.) A possible application of the method, namely, to yield a fully microscopic treatment of

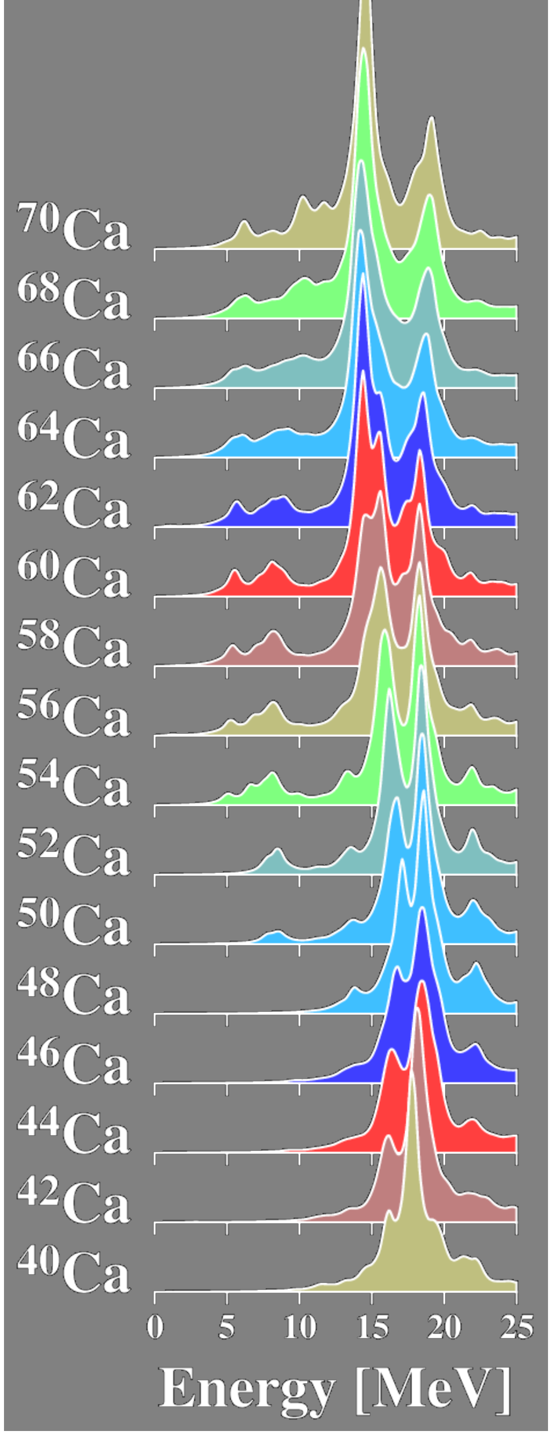
Coming Soon in *Physics*
• Can problems in condensed matter be fixed with string theory tools?
• The electric route to detecting the spin Hall effect

Now in Focus
Measuring the Magnetism of Light
September 24, 2010
Two research teams used a ring-like probe to directly characterize the magnetic field of infrared light in a small cavity.

Feedback
Let us know what you think of *Physics*. Please email

New approach to superfluid nuclear systems

New TDDFT method with time-dependent pairing dynamics was developed, which reduces the computational cost by several orders of magnitude. This may allow a full microscopic description of nuclear fission in future.

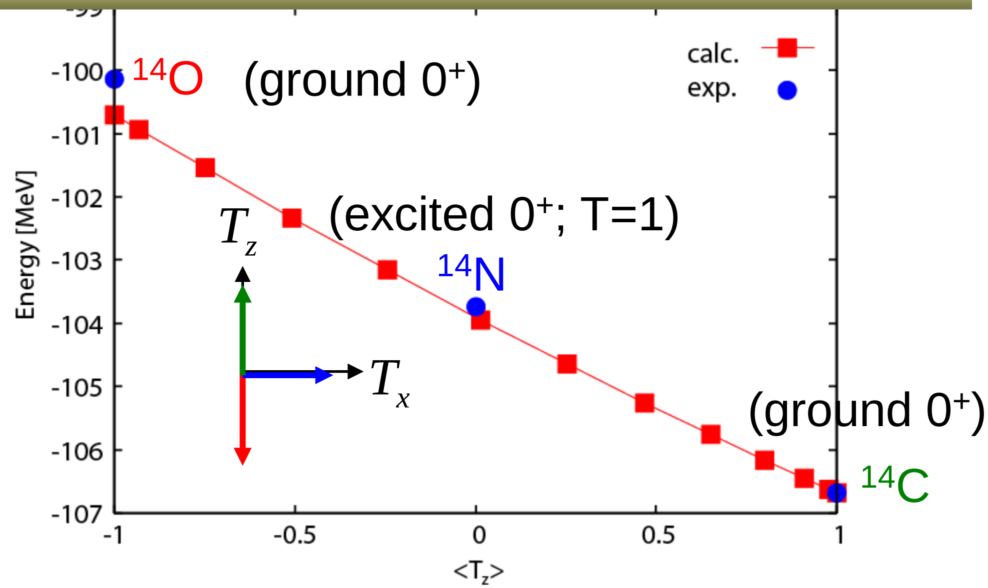


Pygmy dipole states and constraints on symmetry energy

Inakura et al., PRC **80,** 044301 (2009); PRC **84**, 021302(R) (2011)

Pygmy dipole states are one of typical modes of excitation in exotic nuclei. We show that they may provide valuable information on the neutron-skin thickness and density dependence of the symmetry energy.

Proton-neutron-mixing density functional theory



=> K. Sato

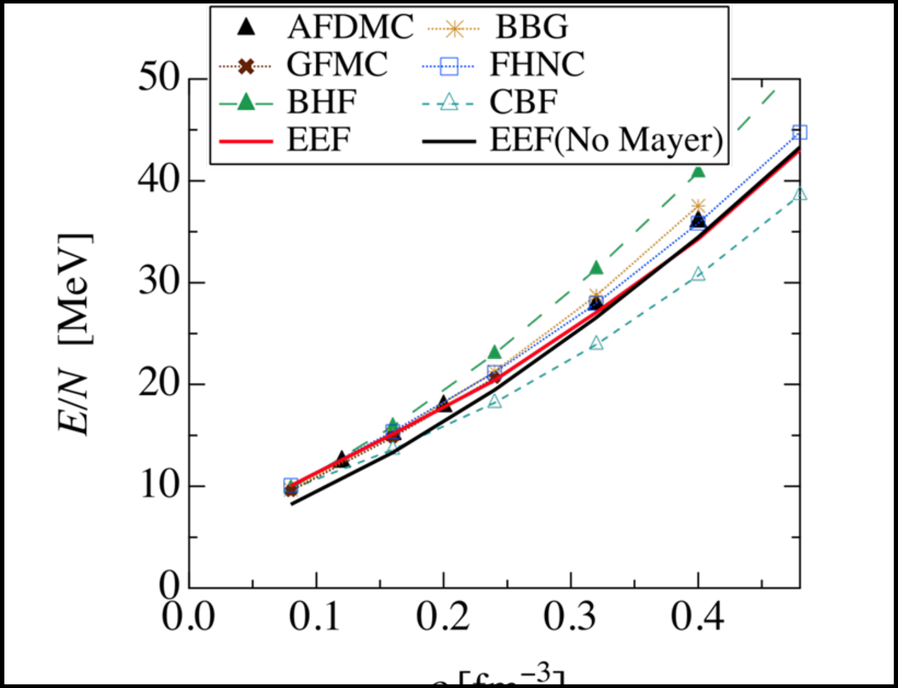
(Thurs.)

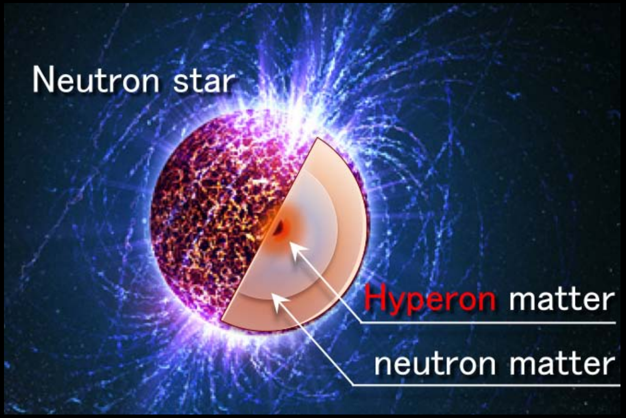
A computer program of a new nuclear DFT has been developed based on a “iso-rotational” invariant energy density functional. This will be further utilized in study the isoscalar (T=0) pairing and charge-exchange reaction.

Nuclear and SN EOS

Variational Method by Takano et al.

- finite T
- asymmetric matter





Progress of the Research (2008-2012)

Construction of a nuclear EOS for supernovae (SNe) with the cluster variational method (In progress)

Method

The **cluster variational method** with AV18+UIX for **uniform matter**.
The **Thomas-Fermi method** for **non-uniform matter.**

Collaboration with A03-group

Yamamuro, Nakazato, Suzuki (Tokyo Univ. Sci.)

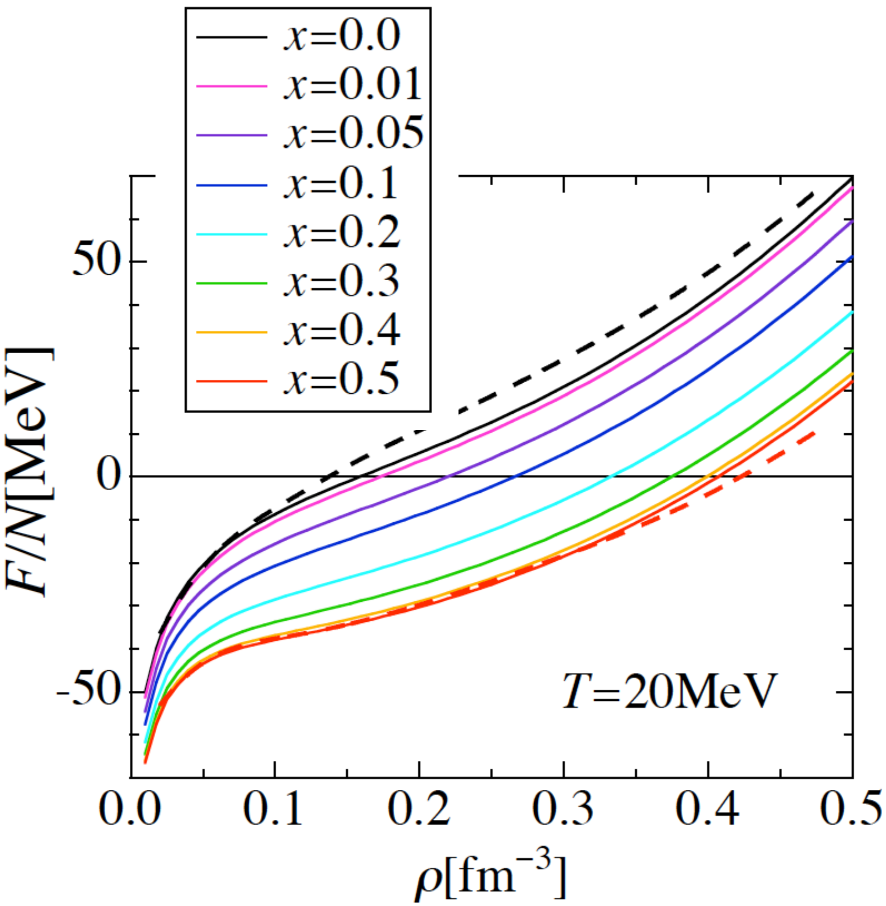
Numerical calculations of the free energies for various densities, temperature and proton fractions: **~ 10^7 points**

Supported by A04-group

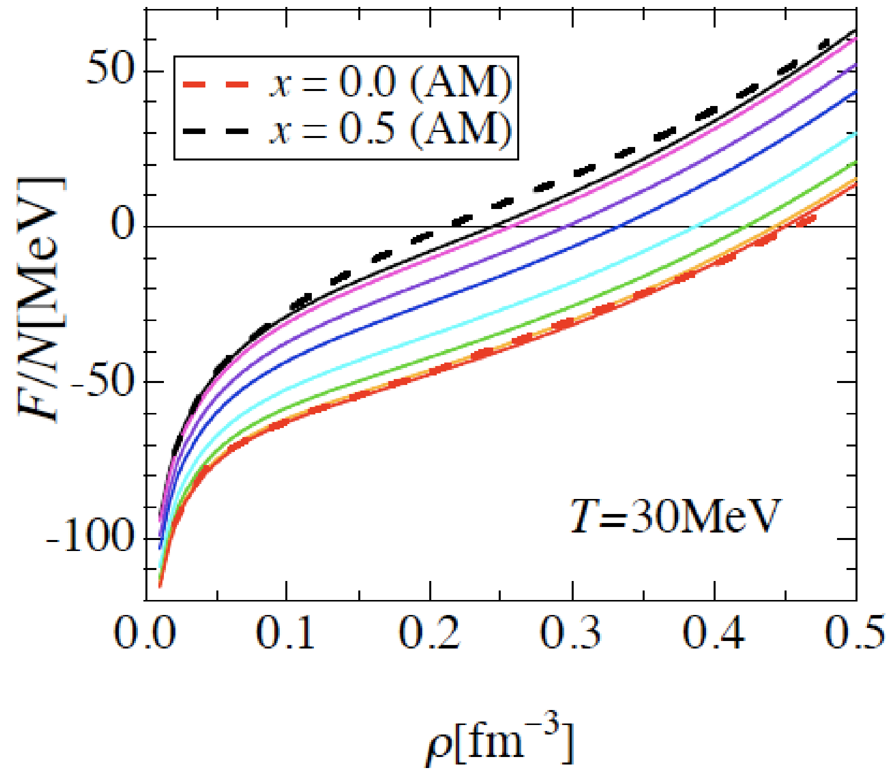
Matsufuru(KEK)

A part of the energy is calculated with GPU: ~100 times faster!

The SN-EOS with the cluster variational method



→ Togashi (Fri.)

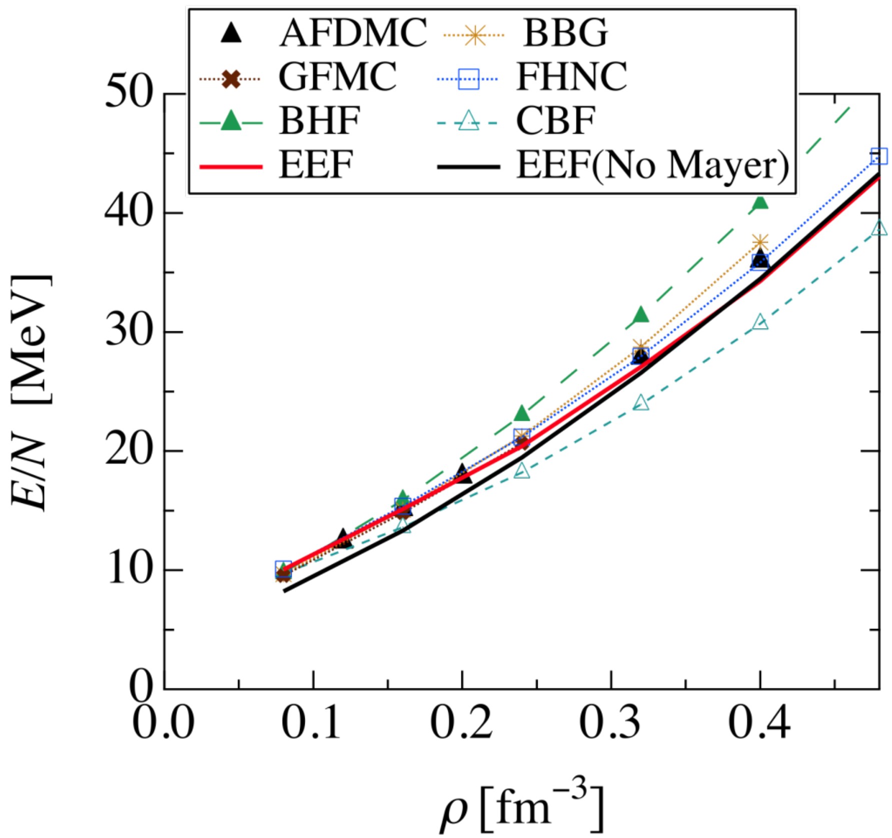


The free energy of hot asymmetric nuclear matter is calculated with the method by Schmidt and Pandharipande, toward a **SN-EOS**.

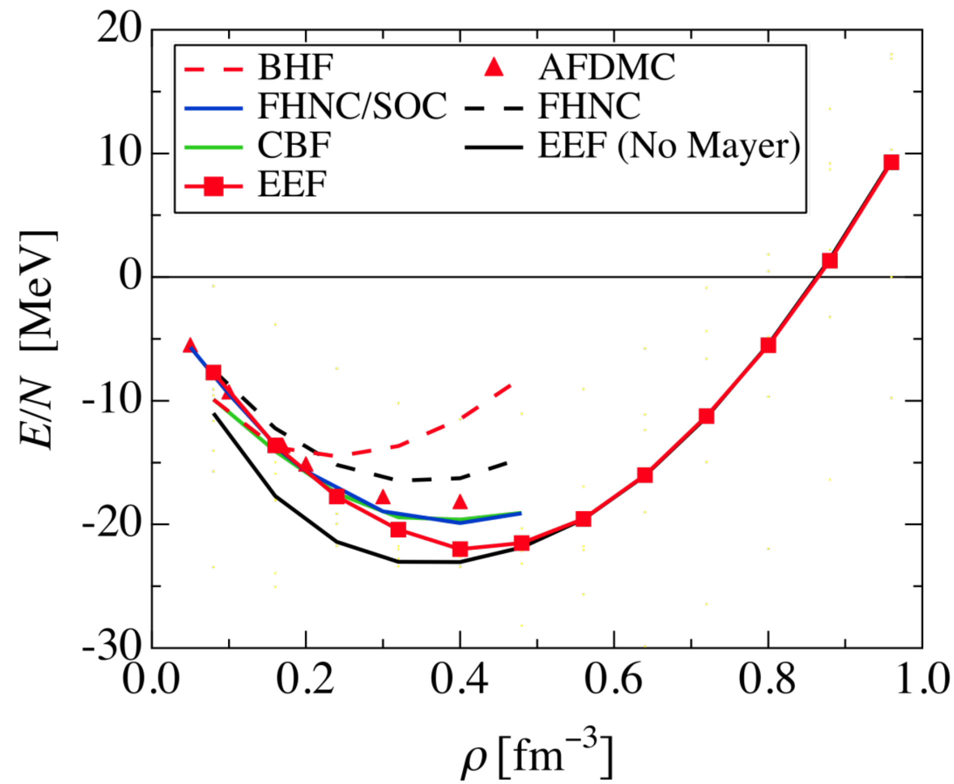
AM: A. Mukherjee, PRC79(2009)045811.

Variational method with the explicit energy functional

→ Takano (poster)



Pure Neutron Matter



Symmetric Nuclear Matter

(Preliminary)

The v6' potential

Reasonable energies are obtained

Dense LQCD

Reduction Formula for Wilson Fermion Determinant

K.Nagata and A. Nakamura, Phys. Rev. D82, 094027 (2010)

$$\frac{\det \Delta(\mu)}{\det \Delta(0)} = \frac{\det(\xi + Q)}{\det(1+Q)} \qquad \xi \equiv e^{-\mu/T}$$

(fugacity)

Q is $(4N_cN_xN_yN_z) \times (4N_cN_xN_yN_z)$ matrix. No N_t !

Diagonalize Q,

$$Q \to \begin{pmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \cdots & \\ & & & \lambda_{N_{red}} \end{pmatrix}$$

$$\det(\xi + Q) = \prod(\xi + \lambda_n)$$

λ_n does not depend on μ.

Make a Good Tool !

Summary (2008-2012)

- Lattice Study of Finite Density QCD
  - Wilson Fermions with improved Gauge and Fermion action
- Fugacity Expansion Formula, 2010 [**PRD82,094027(2010)]**

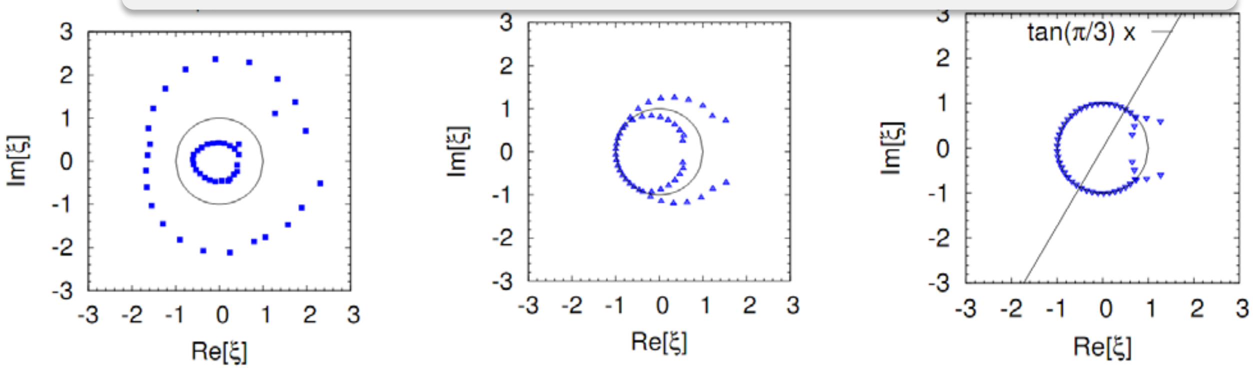
  - Fermion matrix size reduction (CPU time reduction)
  - Useful
    - in the Multi-Parameter Reweighting
    - to Lee-Yang zeros study
    - to calculate higher order Taylor coefficients

Summary continued

- Imaginary Chemical Potential approach, 2011[**PRD83,114507(2011)]**
  - Continuation of the Imaginary chemical potential Phase Boundary to Real chemical potential
- Equation of State, 2012[**JHEP1204,092,(2012)**]
  - Comparison of the Multi-Parameter Reweighting and Taylor Expansion
- Lee-Yang Zeros and Canonical approach, 2012[**PTEP01A103(2012)]**
- Towards Low Temperature and finite density,2012
  - To study Fermion Matrix behavior (eigenvalue behavior) of the reduction fermion matrix
  - To analyze how to take the limit towards Low temperature, Finite density and Thermo-dynamical state

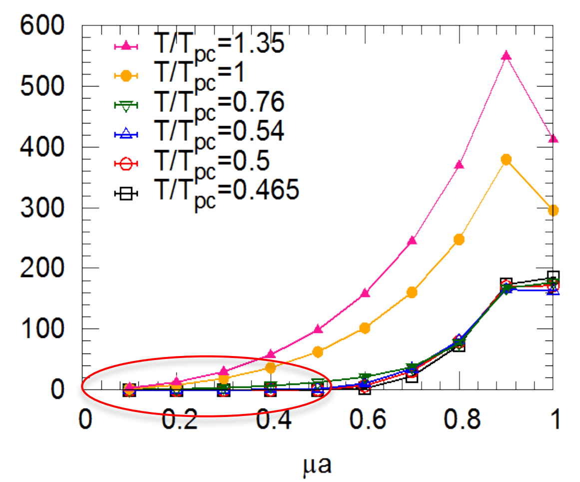
Highlights (2008-2012)

- Lee-Yang Zero [**PTEP01A103(2012)**]
  - Zeros in Complex Fugacity plane
  - Reflects Phase Structure



At low T, two circles (baryon and anti-baryon)
At high T, they merge into one unit circle.

Nagata (Sat.) ←



Summary of A02 achievements

PTEP
Progress of Theoretical and Experimental Physics

Progress of Theoretical and Experimental Physics, (2012) special volume
"Computational Approaches in Particle, Nuclear and Astrophysics"
http://www.oxfordjournals.org/our_journals/ptep/special_issue_a.html

- **Lattice quantum chromodynamical approach to nuclear physics**
  HAL QCD Collaboration, *Prog. Theor. Exp. Phys.* (2012) 01A105.

- **Towards extremely dense matter on the lattice**
  XQCD-J Collaboration, *Prog. Theor. Exp. Phys.* (2012) 01A103.

- **Gaussian expansion method for few-body systems and its applications to atomic and nuclear physics**
  E. Hiyama, *Prog. Theor. Exp. Phys.* (2012) 01A204

- **New-generation Monte Carlo shell model for the K computer era**
  N. Shimizu et al., *Prog. Theor. Exp. Phys.* (2012) 01A205

- **Density functional approaches to collective phenomena in nuclei: Time-dependent density functional theory for perturbative and non-perturbative nuclear dynamics**
  T. Nakatsukasa, *Prog. Theor. Exp. Phys.* (2012) 01A207.

Advanced Institute for Computational Science (AICS), RIKEN

10 PFlops supercomputer KEI "京" (full operation started on Sep.28, 2012)

http://www.aics.riken.jp/en/

Five "strategic" programs (FY 2011-2015)

1. Life and Medicine
2. New Materials
3. Environment
4. Engineering
5. Particle, Nuclear and Astrophysics

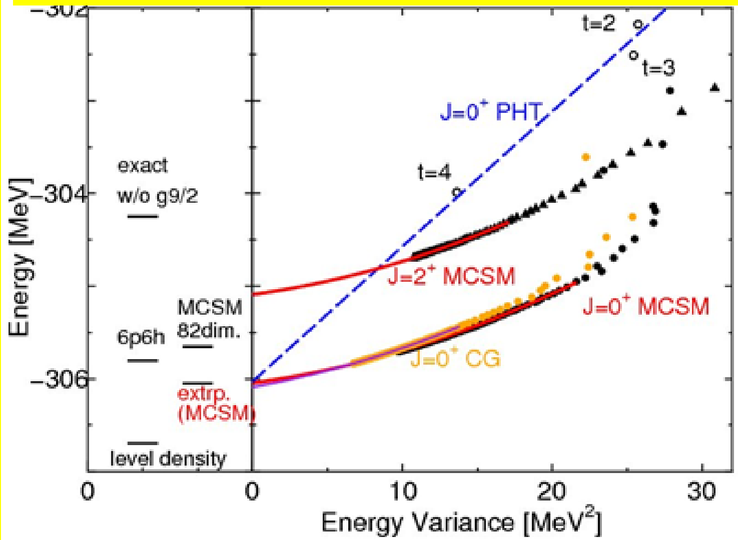
Project 1: Lattice QCD
Project 2: ab initio Nuclei
Project 3: Supernovae
Project 4: First stars and galaxies

LQCD: 96^4 lattice, a=0.1fm, L=9.6fm, m_π=135MeV

→ Yamazaki (fri.)

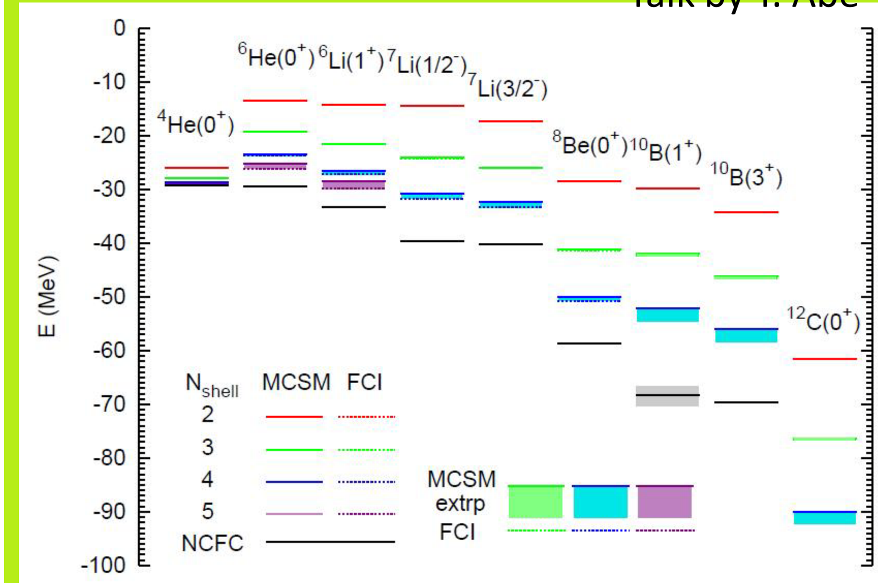
Highlights of the MCSM studies

Energy-variance extrapolation

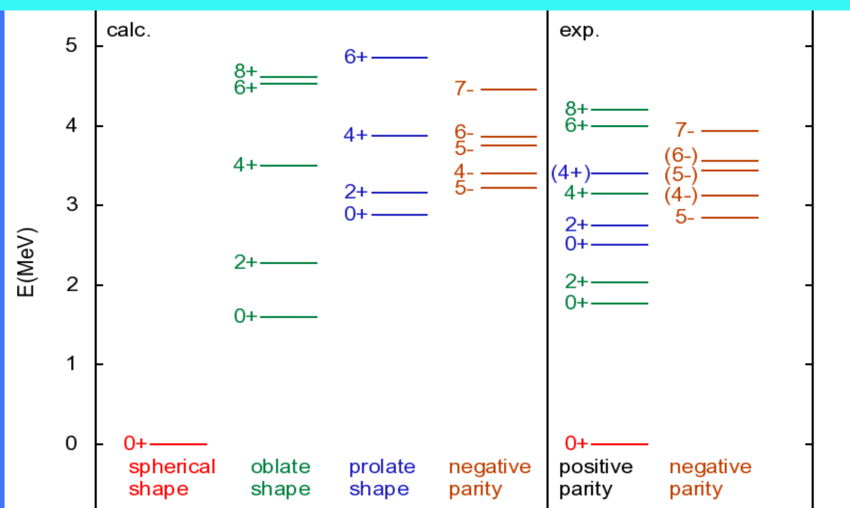


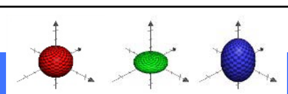
Benchmark calc. in light nuclei

Talk by T. Abe



Level scheme of ^{68}Ni (a doubly magic nucleus)



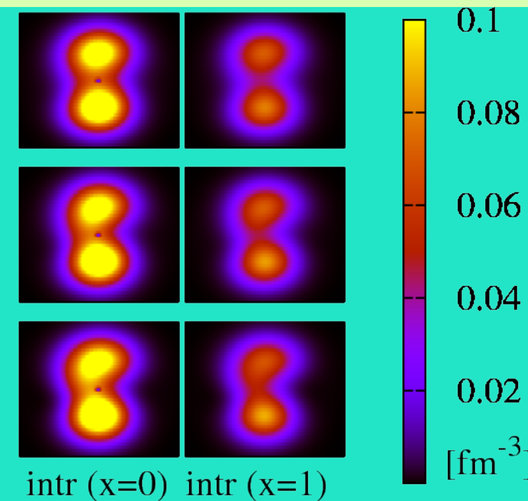


Talk by Y. Tsunoda

$\beta \sim 0.0$ $\beta \sim -0.2$ $\beta \sim 0.4$ (superdeformed)

Intrinsic Density from ab initio calc.

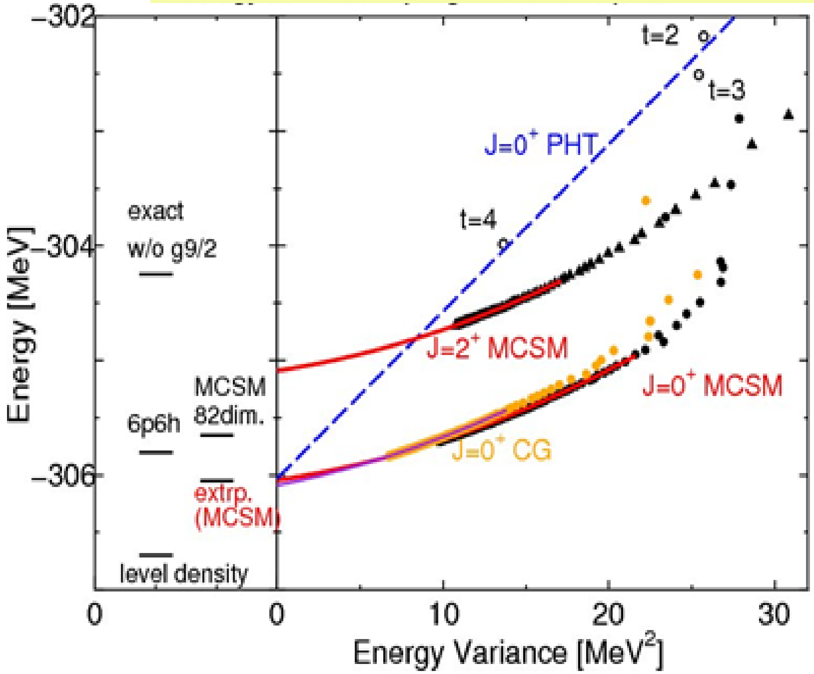
^{8}Be



List of related works（FY 2008-2012）

- Shape transition in exotic Si & S isotopes, Y. Utsuno, T. Otsuka, B. A. Brown, M. Honma, T. Mizusaki, and N. Shimizu, Phys.Rev. C86, 051301 (2012)
- VMU in p-shell nuclei C. Yuan, T. Suzuki, T. Otsuka, F. Xu, and N. Tsunoda, Phys. Rev. C85, 064324 (2012)
- Beta decay for astrophysics T. Suzuki, T. Yoshida, T. Kajino, and T. Otsuka, Phys.Rev. C85, 015802 (2012)
- Renormalization persistency of tensor force in nuclei, N. Tsunoda, T. Otsuka, K. Tsukiyama, and M. Hjorth-Jensen, Phys.Rev. C84, 044322 (2011)
- Electron capture from astrophysical interest T. Suzuki, M. Honma, H. Mao, and T. Otsuka, Phys.Rev. C83, 044619 (2011)
- Novel features of nuclear forces and shell evolution in exotic nuclei, T. Otsuka, T. Suzuki, M. Honma, Y. Utsuno, N. Tsunoda, K. Tsukiyama, and M. Hjorth-Jensen, Phys. Rev. Lett. 104 , 012501 (2010)
- Three-body forces and the limit of oxygen isotopes, T. Otsuka, T. Suzuki, J. D. Holt, A. Schwenk, and Y. Akaishi, Phys.Rev.Lett. 105, 032501 (2010)
- Neutrino-induced reaction for stellar process T. Suzuki, M. Honma, K. Higashiyama, T. Yoshida, T. Kajino, T. Otsuka, H. Umeda, and K. Nomoto, Phys.Rev. C79, 061603 (2009)
- Exotic Magnetic Properties in ^{17}C T. Suzuki, and T. Otsuka, Phys.Rev. C78, 061301 (2008)

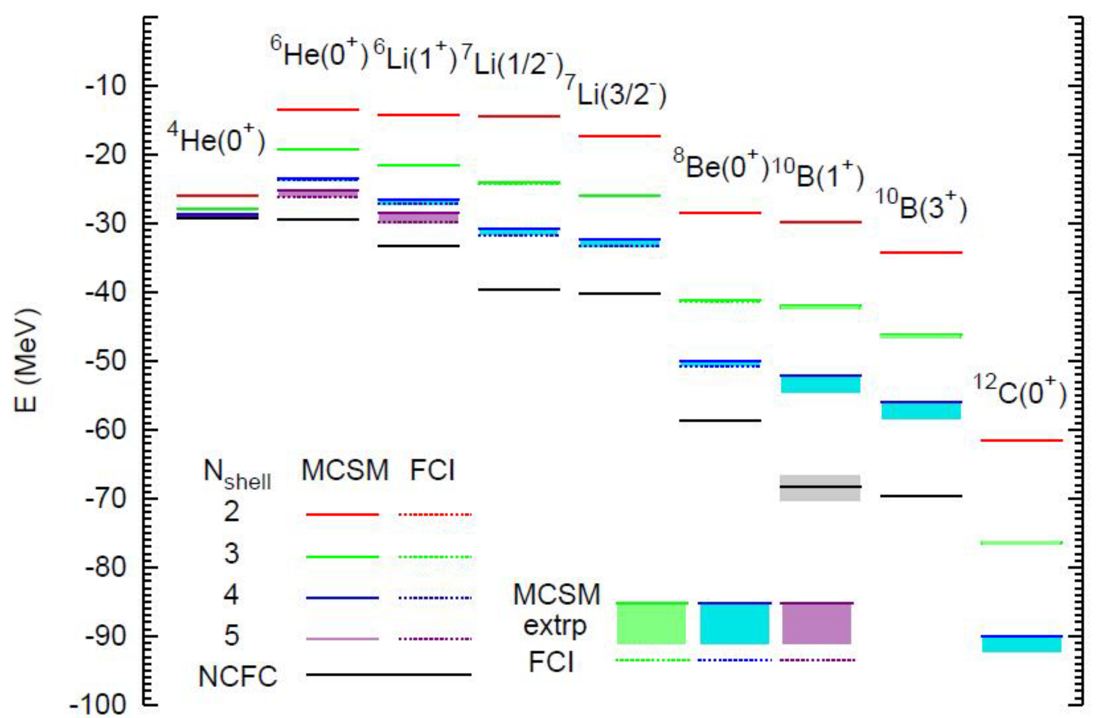
Highlights of the MCSM studies I



Energy-variance extrapolation
- precise estimate of
exact eigenvalues -

Talk by T. Abe

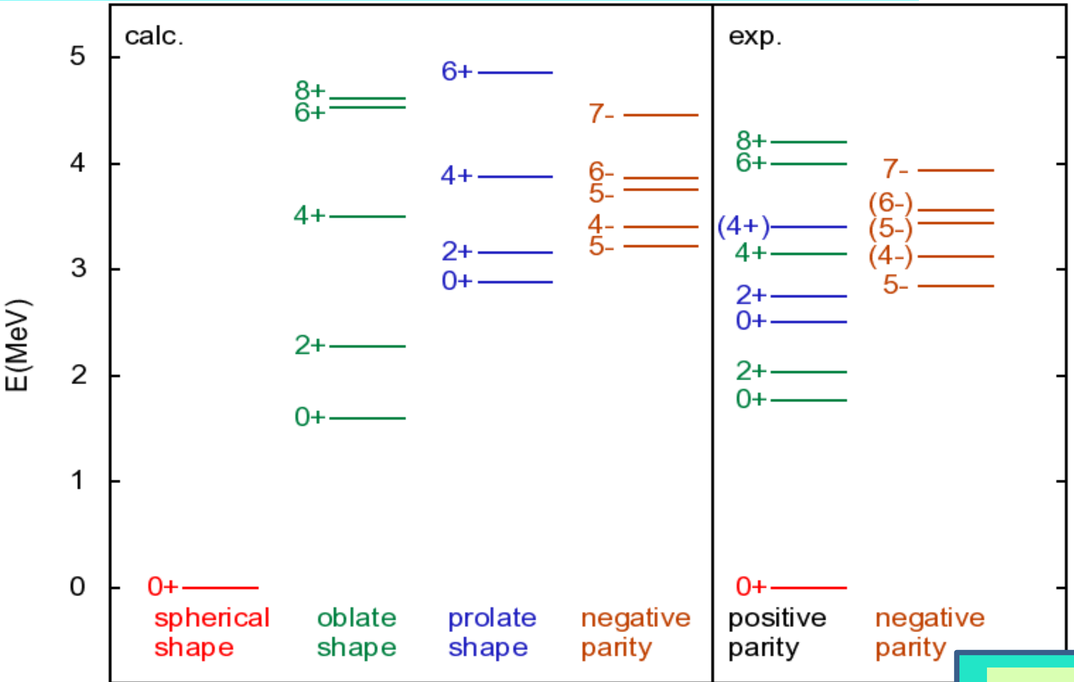
Benchmark calc. in light nuclei
- ready for systematic calcs. -

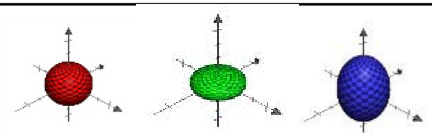


Highlights of the MCSM studies II

Level scheme of ^{68}Ni (a doubly magic nucleus)

Talk by Y. Tsunoda



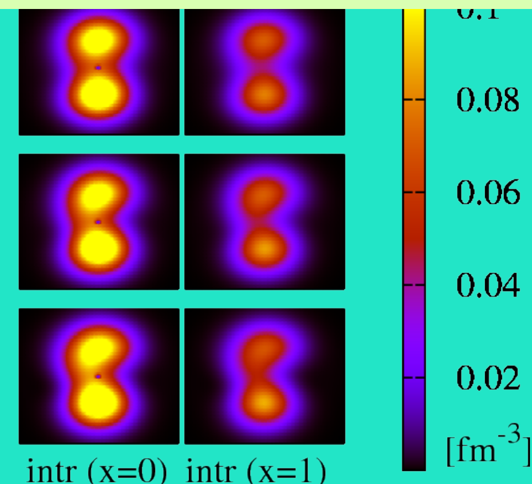


$\beta \sim 0.0$ $\beta \sim -0.2$ $\beta \sim 0.4$ (superdeformed)

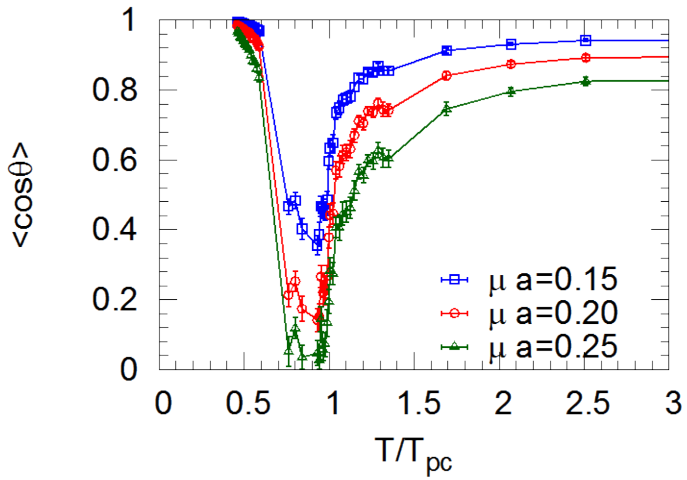
three phases within 3 MeV

Intrinsic Density from ab initio calc.

^{8}Be



Highlights continued

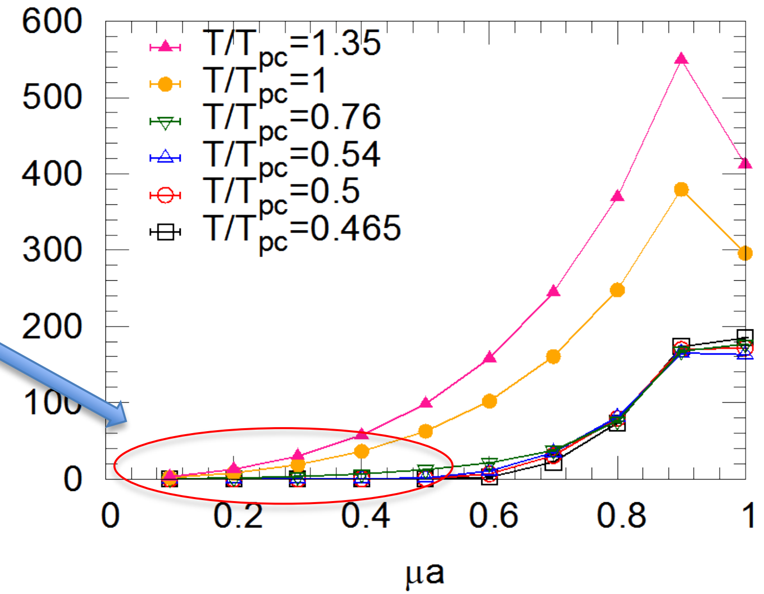


Phase of Fermion Determinant
-- The Origin of the Sign Problem

very sever just below Tc
not sever at low T and

At low temperature,
Fermion Determinants are
insensitive to the chemical
potential up to
This corresponds to
(Silver-Blaze phenomena)
This can be understood from Eigen Value
behavior.

[PTEP01A103(2012)]

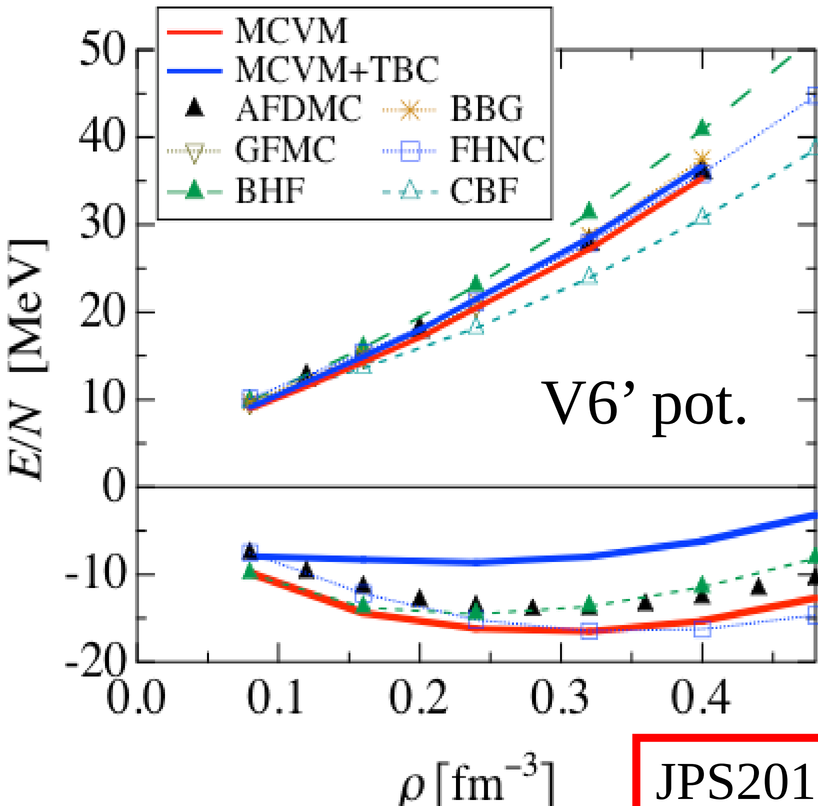


Variational Method with the Energy Functional

Uniform nuclear matter at zero temperature (M. Takano)

The central + tensor forces

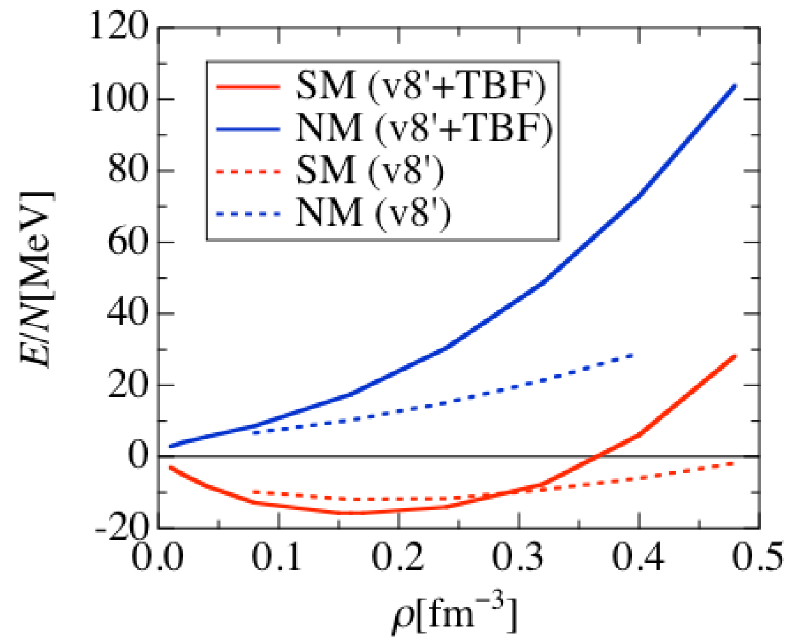
Moderately constrained VM
+
All the three-body cluster terms



JPS2011

Extension to the spin-orbit force

v8' pot. + phenomenological TBF



Two-body part: the tensor and spin-orbit correlations are constrained.

Three-body part: tuned so as to reproduce the saturation point

NUFRA2011

Further refinement is in progress

Progress of the Research (A02: Takano)

Extension of the cluster variational method to Λ hyperon matter:
Collaboration with Hiyama (RIKEN: A02)

In progress

2) Variational method with an explicit energy functional

Poster by Takano

Energy functional for nuclear matter with the v6' potential

Explicit functional of two-body distribution functions

Full minimization

- **Necessary conditions on structure functions** are guaranteed.
- **A main part of the higher-order cluster terms** are included.

The results are reasonable as compared with those with other many-body calculations.

Extensions to the LS force and three-body force are in progress.