格子QCDによる三体力

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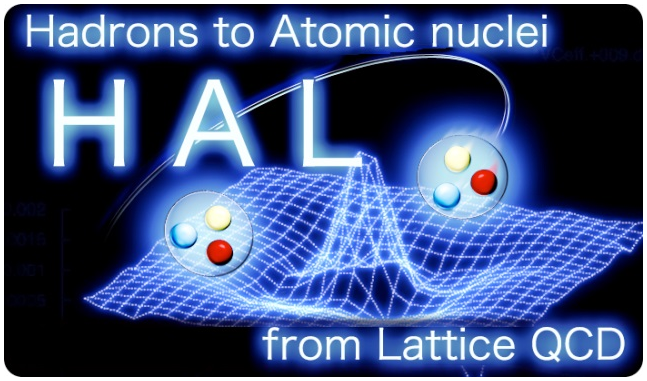
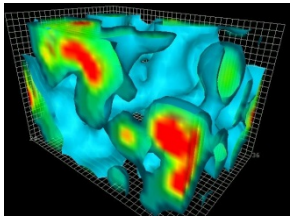
- Motivation
- 3NF in Lat QCD:
  - Framework & comput. algorithm
- Results for 3NF
- Toward physical point calc on K:
  - Code tuning for 3NF & 2BF
- Summary



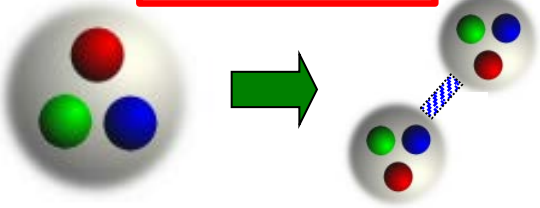
Motivation:

Nuclear Physics and Astrophysics from Lat QCD



QCD Vacuum

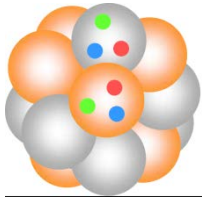
分野5課題1



Baryon

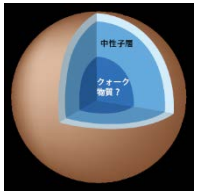
Few-Body

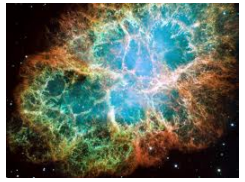
分野5課題2



Nuclei

分野5課題3





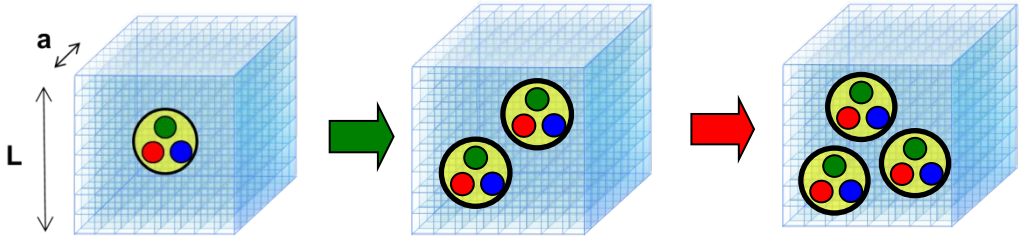
Neutron Star / Supernova

Standard Model

1st-principle lat calc.

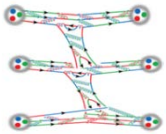
Nuclear Forces

Ab-initio nuclear calc.



1st-principle lat calc.

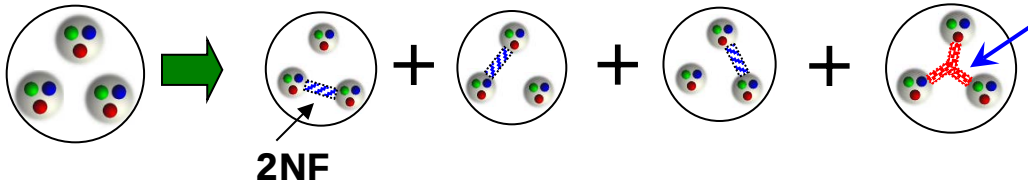
Lattice QCD predictions play a crucial role



Yamazaki et al.

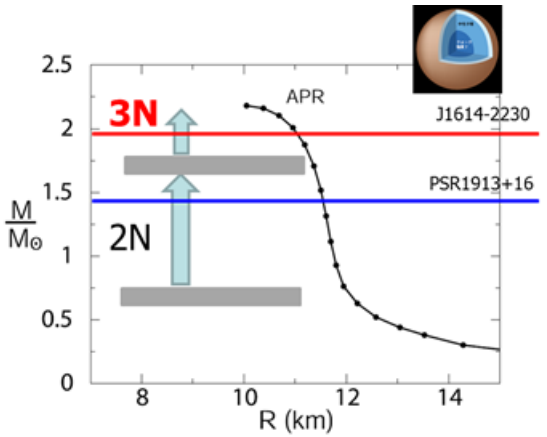
Three-nucleon forces (3NF)

What is 3NF ?



3NF: Forces which cannot be explained by pair-wise 2NF

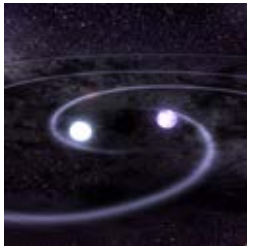
- Essential component for EoS at high density matter



***3NF** also play **significant roles** in*

- *B.E. of light nuclei*
- *Saturation point of nuclear matter*
- *Neutron rich nuclei*
  ↔ *Nucleosynthesis*

RIBF @ RIKEN



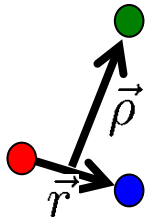
(R.Spero)

Neutron star Merger SuperNova

3NF from NBS wave function [HAL QCD method]

- Nambu-Bethe-Salpeter (NBS) wave function

$$\psi(\vec{r},\vec{\rho}) = \langle 0 | N(\vec{x}+\vec{r}) N(\vec{x}) N(\vec{x}+\vec{r}/2+\vec{\rho}) | 3N \rangle$$



NBS ⟷ Phase shift even in multi-particle system

(non-rela limit)

S.Aoki et al., PRD88(2013)014036

- Obtain 3NF through

$$(E - H_0^r - H_0^\rho)\psi(\vec{r},\vec{\rho}) = \left[\sum_{i<j} V_{ij}(\vec{r}_{ij}) + V_{3NF}(\vec{r},\vec{\rho})\right]\psi(\vec{r},\vec{\rho})$$

by 2N calc

- NBS is obtained by 6pt. correlator

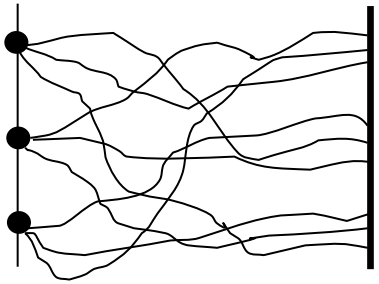
$$G(\vec{r},\vec{\rho},t-t_0) = \sum_{\vec{x}} \langle 0 | N(\vec{x}+\vec{r},t) N(\vec{x},t) N(\vec{x}+\vec{r}/2+\vec{\rho},t) \overline{NNN}(t_0) | 0 \rangle$$

In practical calculation,
we employ **time-dependent HAL QCD method**

N.Ishii et al. (HAL QCD Coll.) PLB712(2012)437

Challenge in multi-baryons on the lattice

- Enormous computational cost for correlators
  - # of Wick contraction (permutations) $\sim [(\frac{3}{2}A)!]^2$
  - # of color/spinor contractions $\sim 6^A \cdot 4^A$ or $6^A \cdot 2^A$



    - **Total cost:**
      - ^{2}H : 9 x 144 = 1 x 10^3
      - ^{3}H : 360 x 1728 = 6 x 10^5
      - ^{4}He : 32400 x 20736 = 7 x 10^8

Improvement:
T.Yamazaki et al.,
PRD81(2010)111504

- **[Unified contraction algorithm (UCA)]** TD, M.Endres, CPC184(2013)117
  - Treat Wick/color/spinor contractions in a unified index space
    - ➔ huge redundancies can be eliminated systematically
    - ➔ permutation finished BEFORE any lattice calc
    - **Significant improvement**

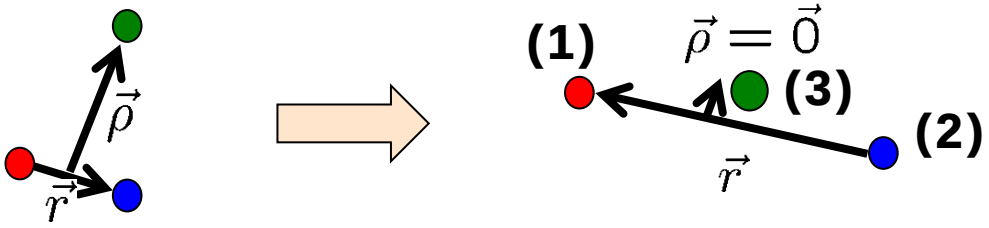
$\times 192$ for ^{3}H/^{3}He, $\times 20736$ for ^{4}He, $\times 10^{11}$ for ^{8}Be (x add'l. speedup)

See also subsequent works: Detmold et al., PRD87(2013)114512
Gunther et al., PRD87(2013)094513

3NF calculation in Lat QCD

- We fix the geometry of 3N (🡐 this is not an approximation)
- We study **linear setup**

We consider Triton channel

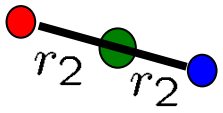


$(\vec{r}_2 \equiv \vec{r}/2)$

  - 🡒 $L^{(1,2)\text{-pair}} = L^{\text{total}} = 0$ or 2 only
  - 🡒 **Bases are only three**, labeled by **$^1S_0$, $^3S_1$, $^3D_1$ for (1,2)-pair**

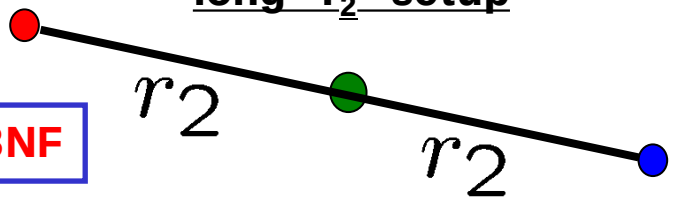
- **Linear setup** with various distance "**r_2**"

short "r_2" setup



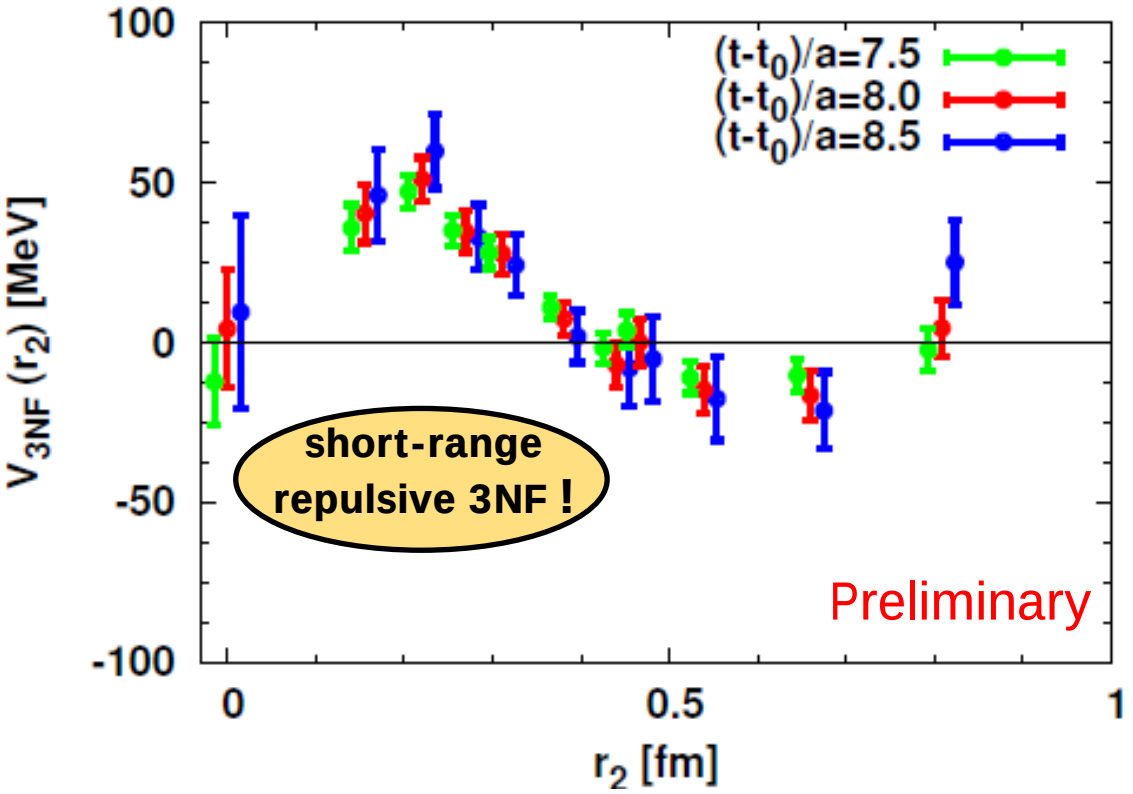
Study r_2-dependence of 3NF

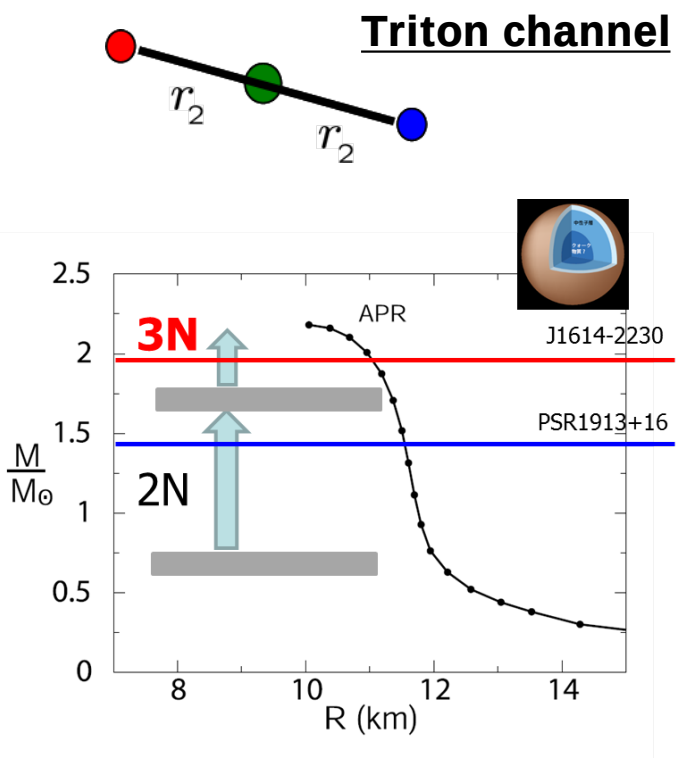
long "r_2" setup



3N-forces (3NF) on the lattice

T.D. et al. (HAL QCD Coll.) PTP127(2012)723
+ t-dep method updates etc.





Nf=2 clover (CP-PACS), 1/a=1.27GeV,
L=2.5fm, $m\pi$=1.1GeV, m_N=2.1GeV

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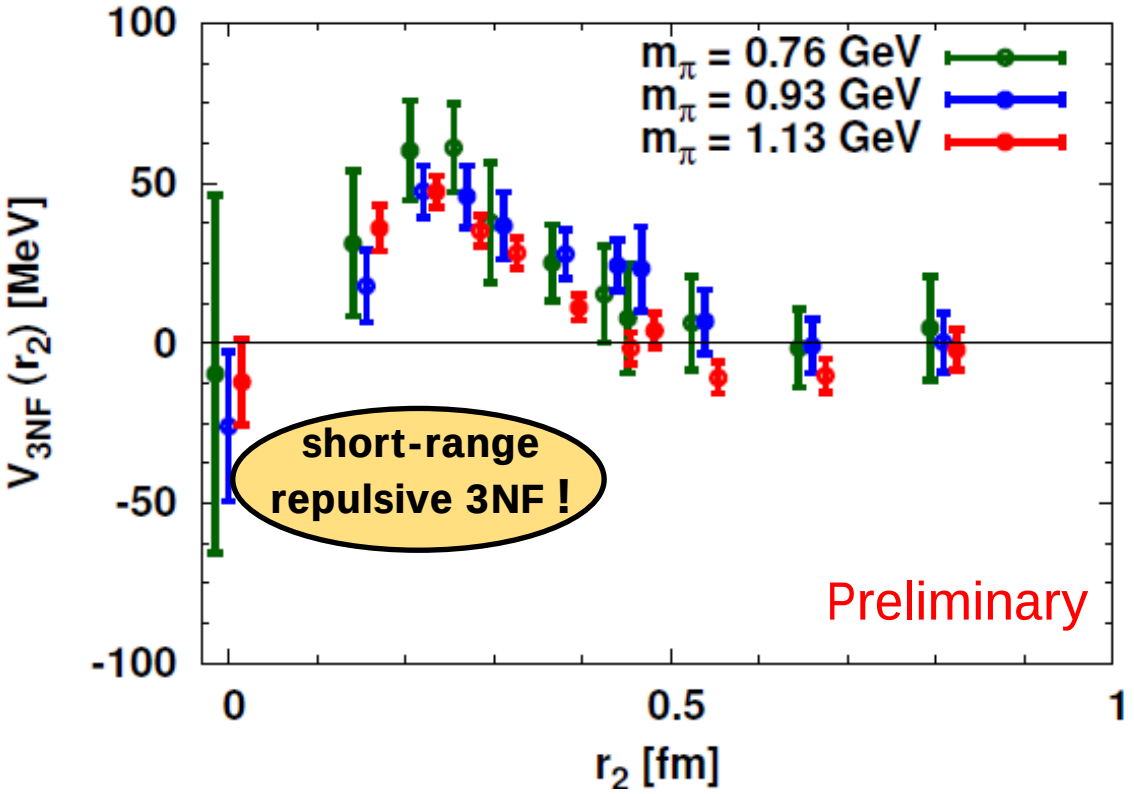
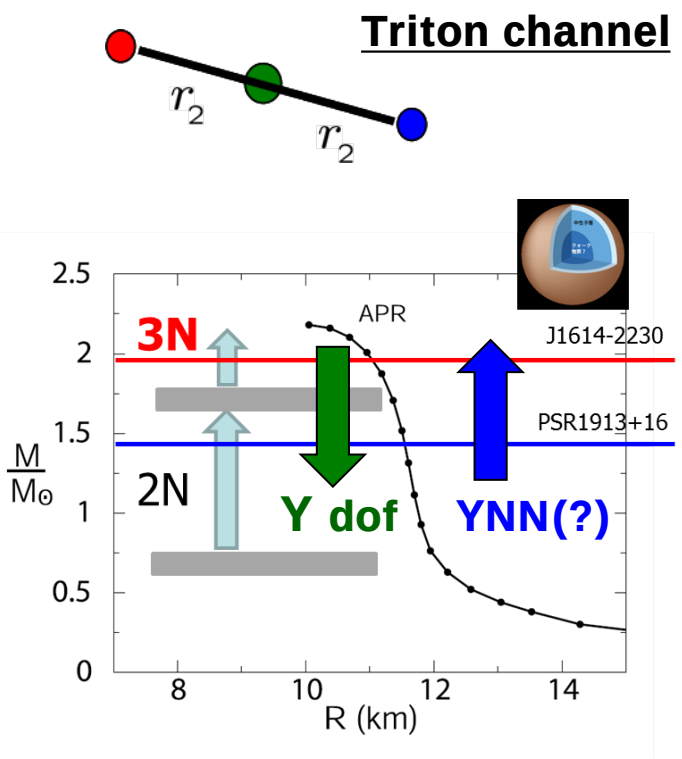




Nf=2 clover (CP-PACS), 1/a=1.27GeV,
L=2.5fm, mπ=0.76-1.1GeV, m_N=1.6-2.1GeV

How about other geometries ?

How about YNN, YYN, YYY ?

Toward physical point calc on K: code tuning status

- Physical quark mass configurations w/ L=9fm on K
  - Configurations in generation
- Comput. of Potential = quark solver + measurement
  - For usual lattice studies, solver is dominant
  - For baryon forces, measurement is very costly
- Measurement
  - Three-nucleon forces (3NF)
    - Very expensive contraction cost, local comput.
  - Two-baryon forces (2BF)
    - Expensive contraction cost by **many coupled channel** systems
    - **FFT cost** by convolution (zero-mom projection for 2-body system)

~x50 calc

Development in FY2013

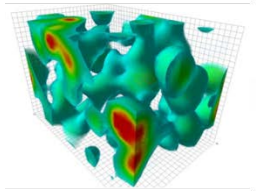
- Extensive refactoring of the code was performed
  - Unified Contraction Algorithm (UCA) for all 2BF: NN/YN/YY (in addition to 3NF)
  - Many FFT are bundled to reduce the latency
  - Better implementation of OpenMP & cache tuning/SIMD
    - (Found a lot of system bugs (FX10/Kei, BG/Q, SR16000, etc.))
  - 2BF: ~ x10-x100
  - 3NF: ~ x1000

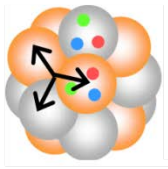
speedup

3NF: efficiency = 18% @ 2048node

- Comput. Cost as of the end of FY2013
  - Target: 96^4 in 2048node
  - Measurement (2BF): ~5mins for 16x2 time slices
  - Solver: ~16mins w/o AMA, ~4mins(?) w/ AMA
  - ➔ measurement code becomes reasonably fast

Summary and Prospects





- Hadron Interactions by 1st principle Lat calc
  - Bridging different worlds:
    Particle Physics / Nuclear Physics / Astrophysics
- Frontier: Three-Nucleon Forces (3NF)
  - **NBS wave func. carries proper phase shifts !**
  - Breakthrough in compt. cost [unified contraction algorithm]
  - Repulsive 3NF at short distance observed
- **On the K computer:**
  - UCA implemented for all 2BF & other code tunings

➔ **Measurement reasonably fast**
➔ **Physical quark mass calc**