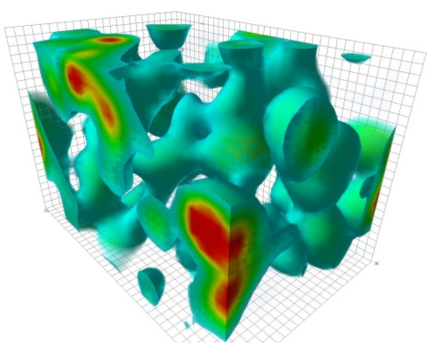
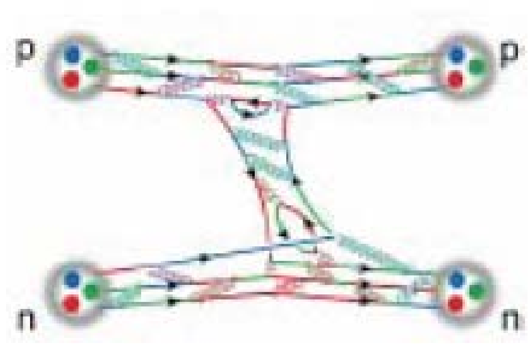
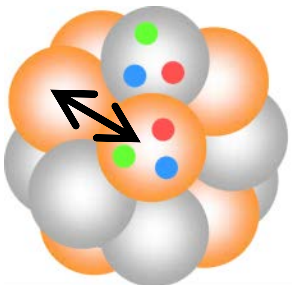
格子QCDによる原子核物理

Takumi Doi

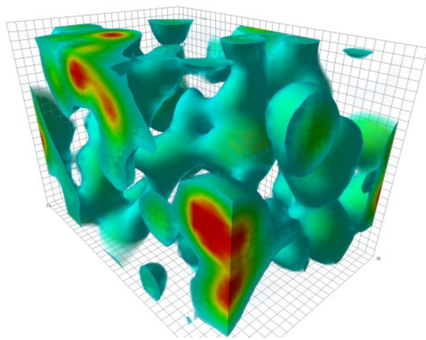
(Nishina Center, RIKEN)

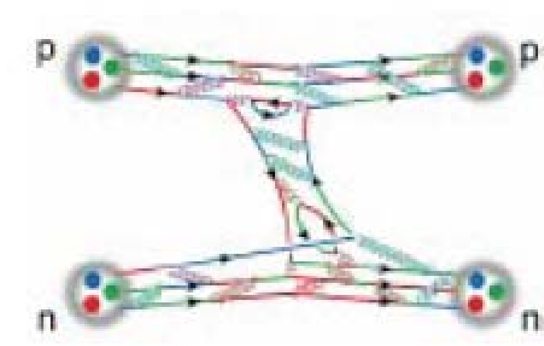


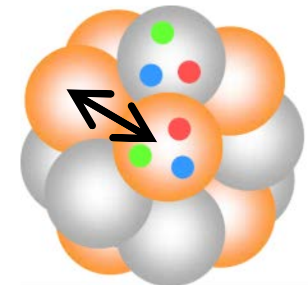




Particle Physics | **Nuclear Forces** | **Nuclear Physics**



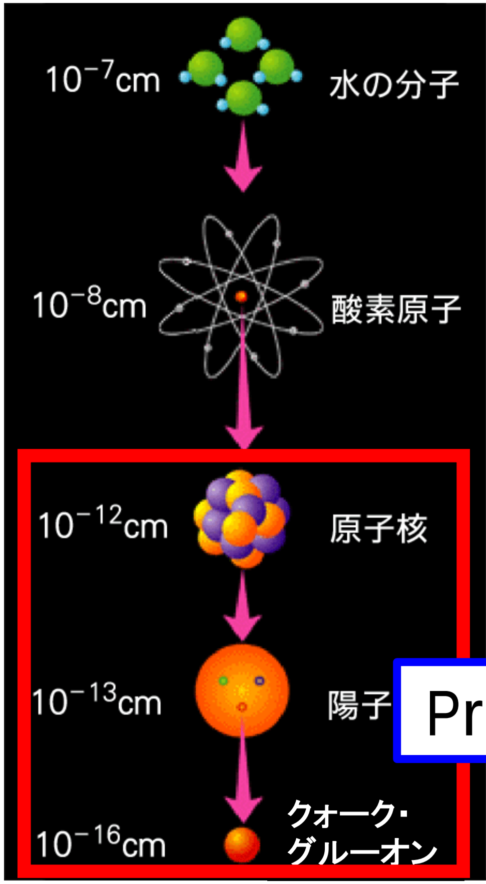




- **<u>Outline</u>**
  - Introduction
  - Nuclear forces by Lattice QCD simulations
  - Lattice results on the eve of the K-computer
  - Project on the K-computer
  - Summary & Prospects

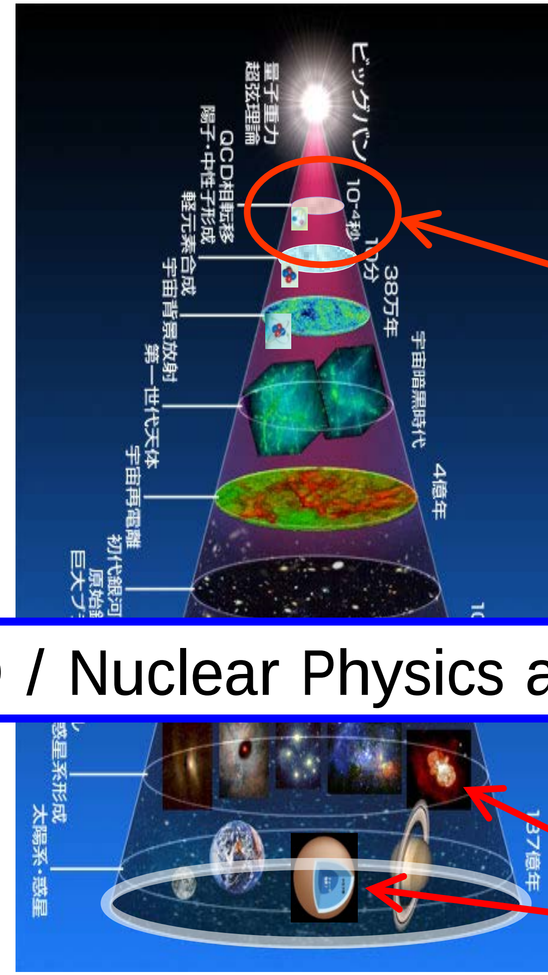
What does matter consist of ?

Where do we come from ?
Where are we going ?



Strong interaction (QCD=Quantum Chromo Dynamics)

<u>4 fundamental forces</u>
- gravity
- EM interaction
- weak interaction
- strong interaction



QCD phase transition

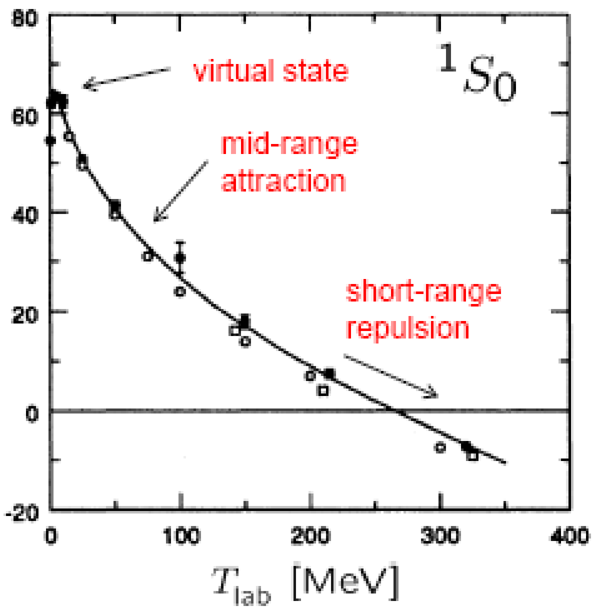
Predictions from QCD / Nuclear Physics are crucial

SuperNova

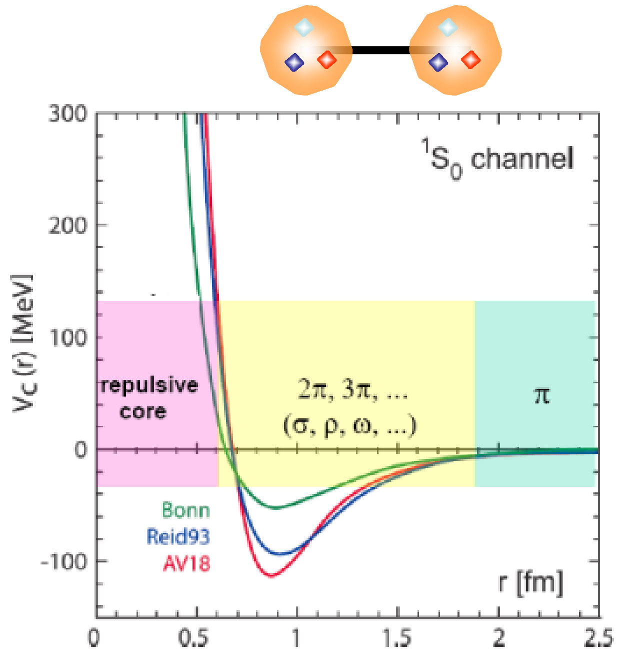
Neutron Star

Nucleosynthesis

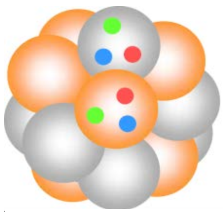
Traditional nuclear physics (DoF=nucleons)



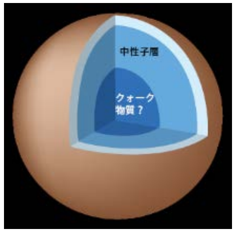
NN phase shifts
from experiments



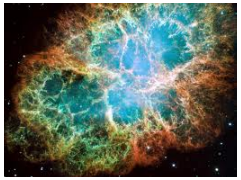
Phenomenological
Nuclear Forces



Nuclei



Neutron Stars



Super Novae

Various
applications

- ***Nuclear Forces*** ***play crucial roles***
  - ***Yet, no clear connection to QCD so far***

QCD (DoF=quarks/gluons)

- Formula of QCD: very simple & beautiful

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\left[\gamma^\mu (i\partial_\mu - g A_\mu) - m\right] q$$

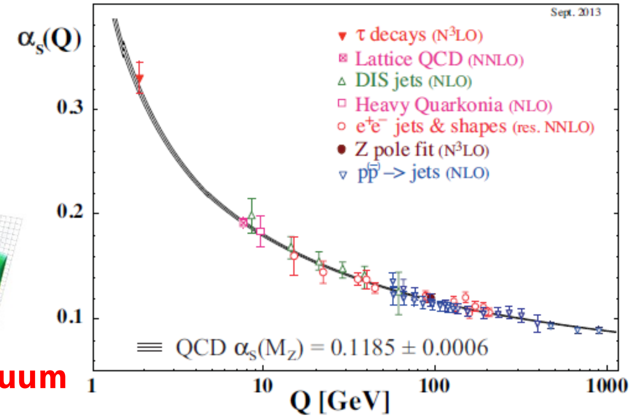
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

  - Only 4 parameters

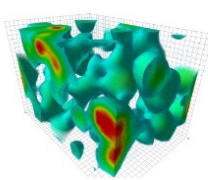
quark masses (m_u, m_d, m_s)
coupling constant $\alpha_s = g^2/4\pi$

mass ($\overline{MS}$, $\mu = 2$GeV)	m_u	m_d	m_s
[MeV]	$2.3^{+0.7}_{-0.5}$	$4.8^{+0.5}_{-0.3}$	95 ± 5

(PDG2013)



- Solving QCD: very challenging
  - Coupling is “strong” at low energy
  - Nonperturbative effects
  - Quantum effects w/ infinite # of DoF

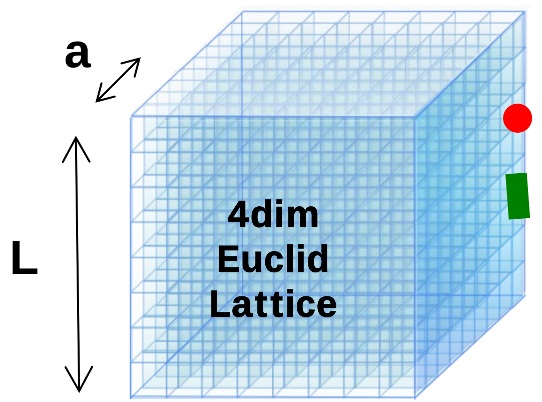


QCD vacuum

「現在でも核力の詳細を基本方程式から導くことはできない。･･･
いわば複雑な高分子の性質をシュレーディンガー方程式から出発
して決定せよというようなもので、むしろこれは無理な話である。」
南部陽一郎 「クォーク」（1997）

Lattice QCD
First-principles calculation of QCD

$$Z = \int dU\, dq\, d\bar{q}\ e^{-S_E}$$



quarks on sites

$$q(x)$$

gluons on links

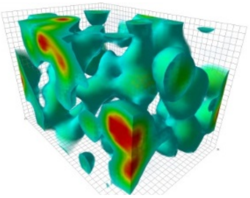
$$U_\mu(x, x+\mu) = \exp[-iaA_\mu]$$

K.G. Wilson

- **Well-defined reguralized system (finite a and L)**
- **Gauge-invariance manifest**
- **Fully-Nonperturbative**
- **DoF ~ 10^9 ➔ Monte-Carlo w/ Euclid time**

Procedure in Lat QCD calc

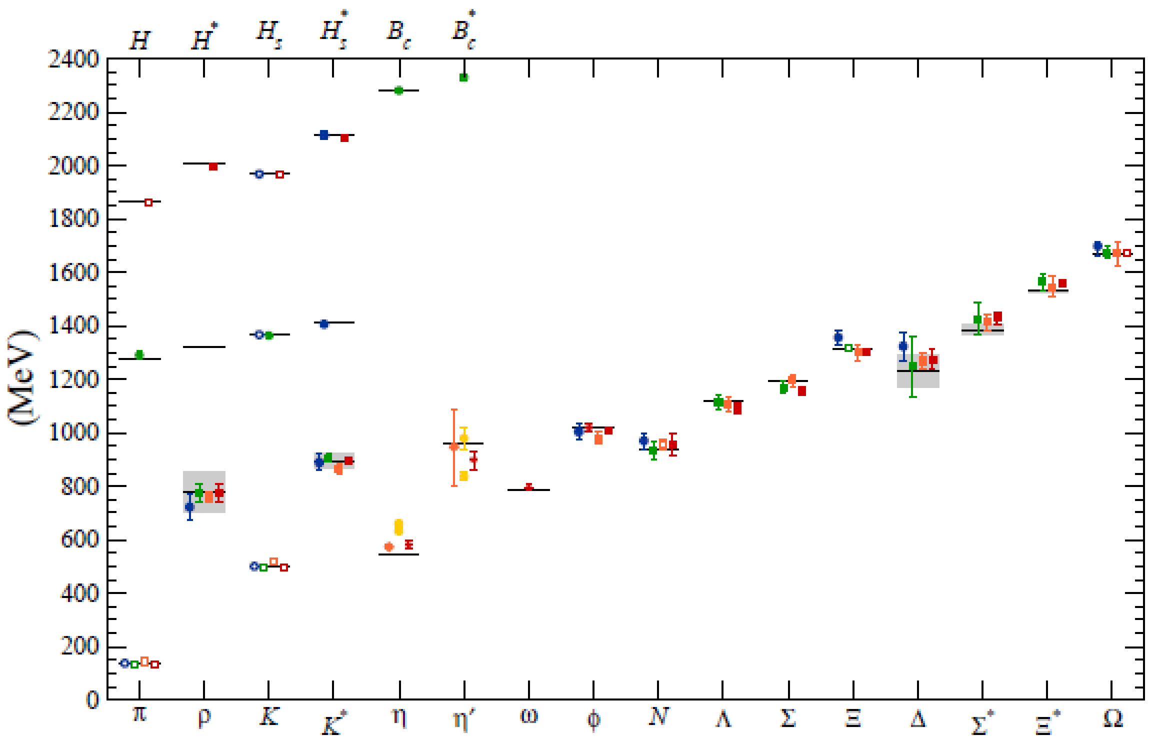
(1) Generate QCD Vacuum (configurations) ➔



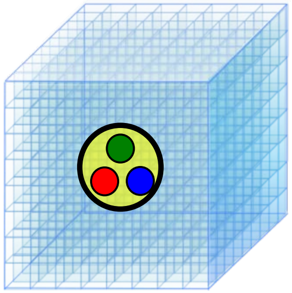
➔ (2) "Measurement" on the QCD Vacuum

Status of Lattice QCD

Hadron spectrum well reproduced !



Summary by Kronfeld, arXiv:1203.1204



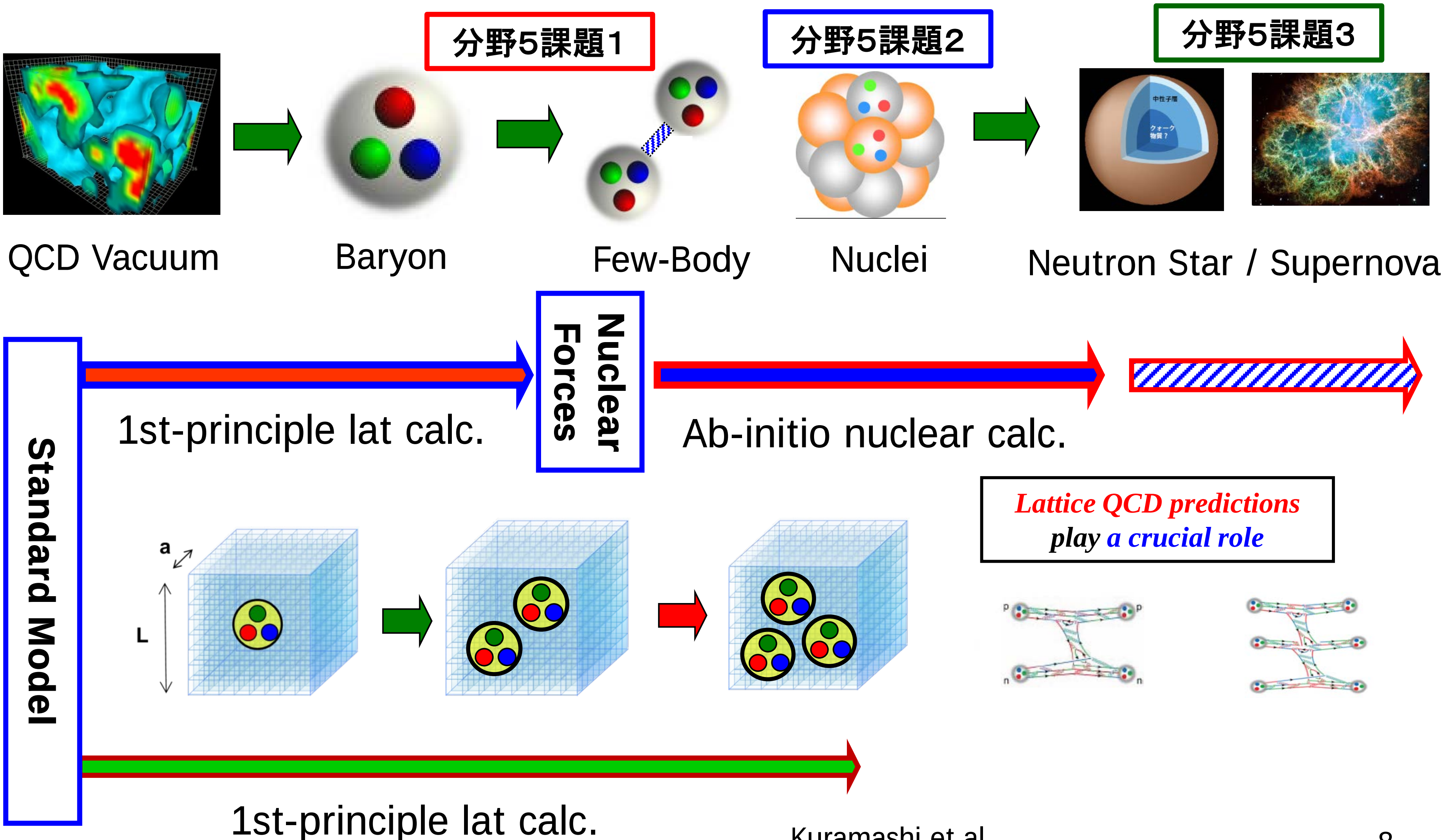
Inputs:

- **quark masses (m_u, m_d, m_s)**
- **coupling constant $\alpha_s = g^2/4\pi$**

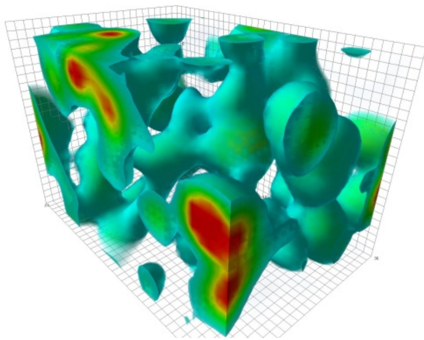
Fully dynamical (unquenched) QCD simulations
at the physical quark mass point already performed

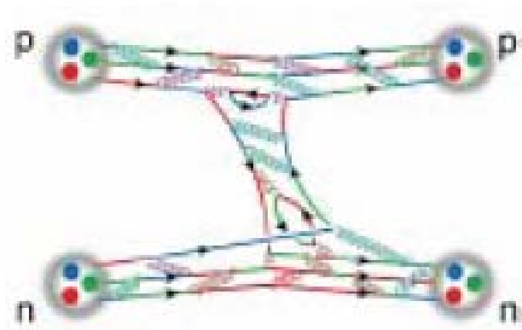
PACS-CS Coll., PRD81(2010)074503
BMW Coll., JHEP1108(2011)148

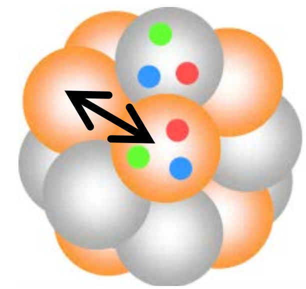
Roadmap:
Nuclear Physics and Astrophysics from Lat QCD



Kuramashi et al.







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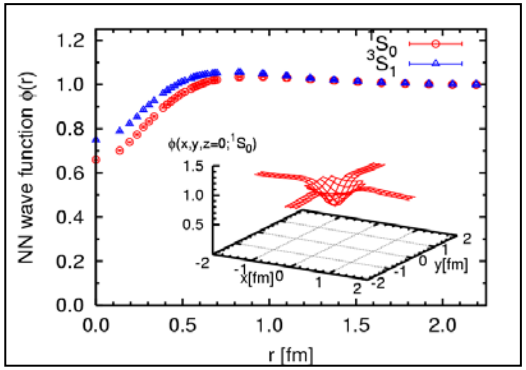
Hadrons to Atomic nuclei HAL from Lattice QCD

S. Aoki, K. Murano (YITP)
N. Ishii, H. Nemura, K. Sasaki, M. Yamada (Univ. of Tsukuba)
B. Charron (Univ. of Tokyo)
T. Doi, T. Hatsuda , Y. Ikeda (RIKEN)
T. Inoue (Nihon Univ.)
F. Etminan (Univ. of Birjand)

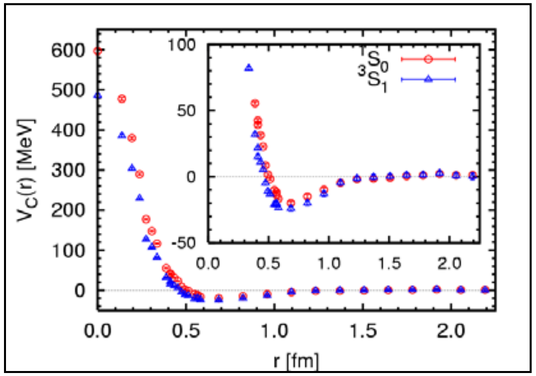
HAL QCD method

Lattice QCD

NBS wave func.



Lat Nuclear Force



$$\psi_{NBS}(\vec{r}) = \langle 0|N(\vec{r})N(\vec{0})|N(\vec{k})N(-\vec{k}), in\rangle$$
$$\simeq e^{i\delta_l(k)} \sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

(at asymptotic region)

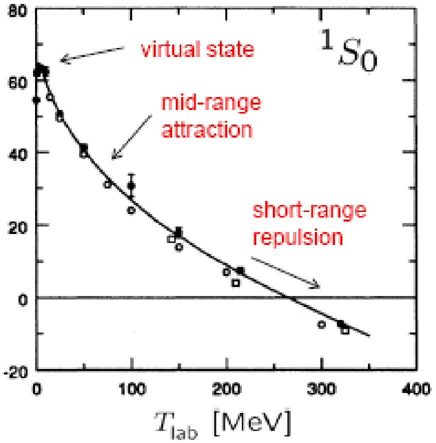
$$(k^2/m_N - H_0)\, \psi(\vec{r}) = \int d\vec{r}'\, U(\vec{r}, \vec{r}')\psi(\vec{r}')$$

Lat potential is faithful to phase shift by construction

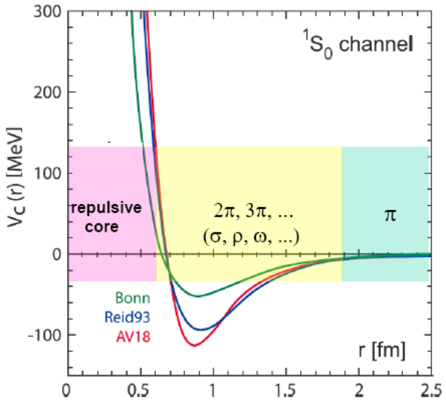
Analog to …

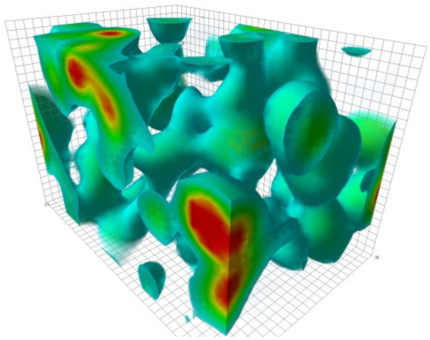
Scattering Exp.

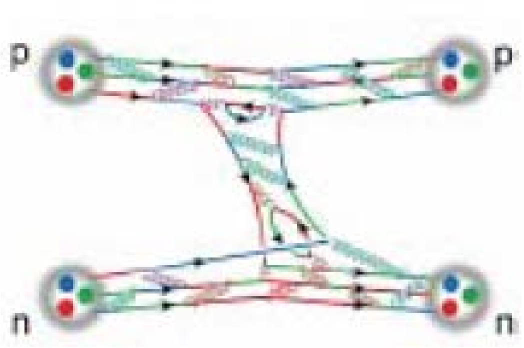
Phase shifts

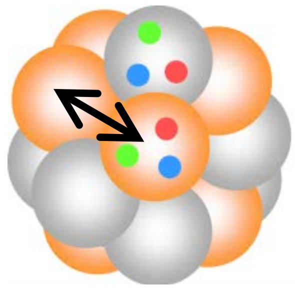


Phen. Potential









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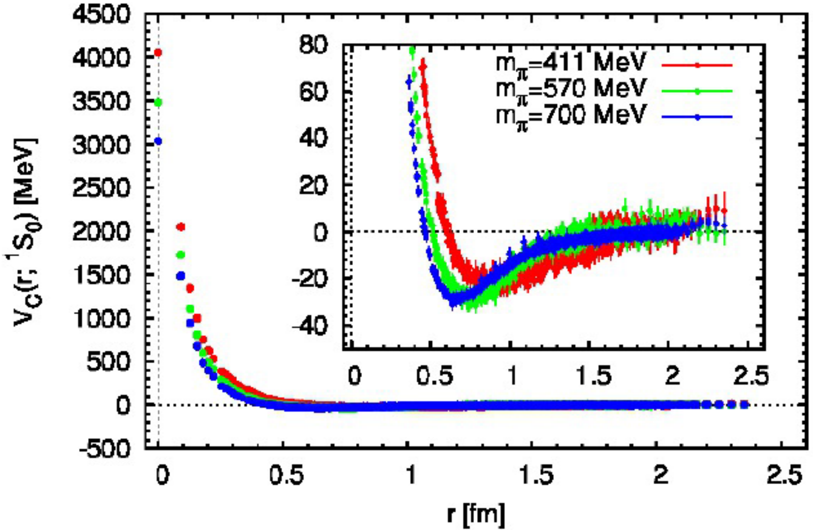
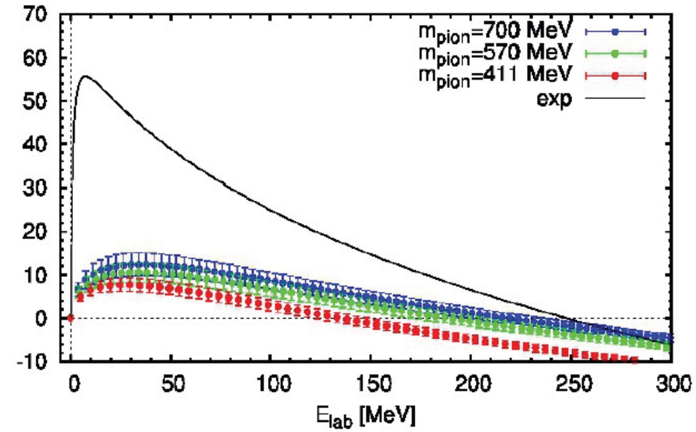
Quark masses are heavy

Nuclear Forces (positive parity) $^{2S+1}L_J$

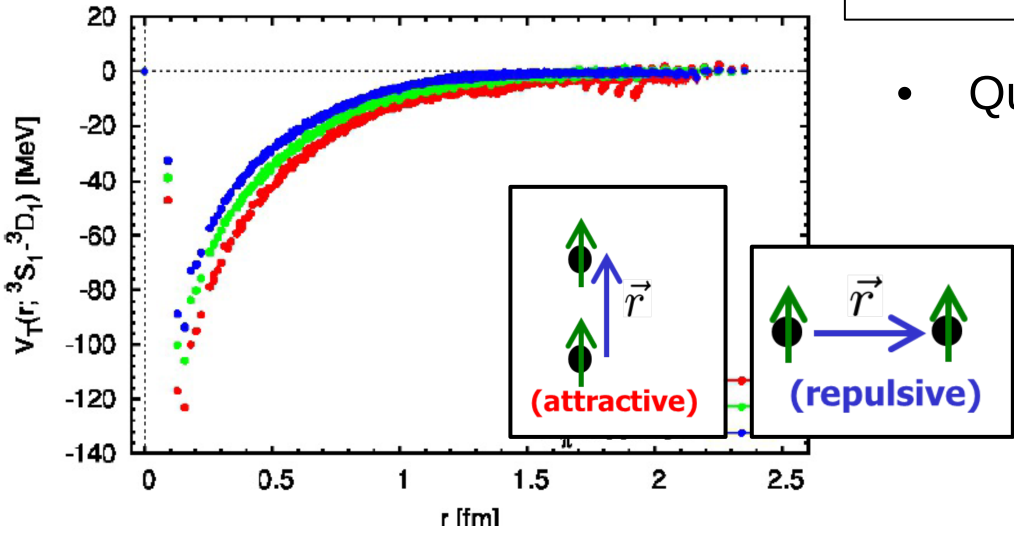
Central in $^1S_0$



Phase shift in $^1S_0$



Tensor in $^3S_1$-$^3D_1$



$$m_\pi(lat) = 0.4 - 0.7 \text{ GeV}$$
$$\text{vs. } m_\pi(phys) = 0.14 \text{ GeV}$$

- Qualitatively reasonable behavior

Not Bound

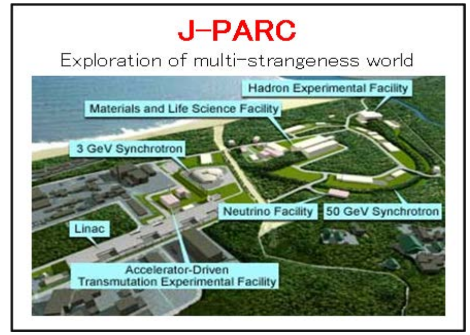
For both of di-neutron & deuteron

N.Ishii @ Lat2012

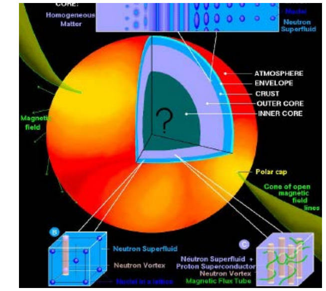
Hyperon forces : Lattice prediction awaited

Nucleons : u, d quarks
Hyperons : u, d, s quarks

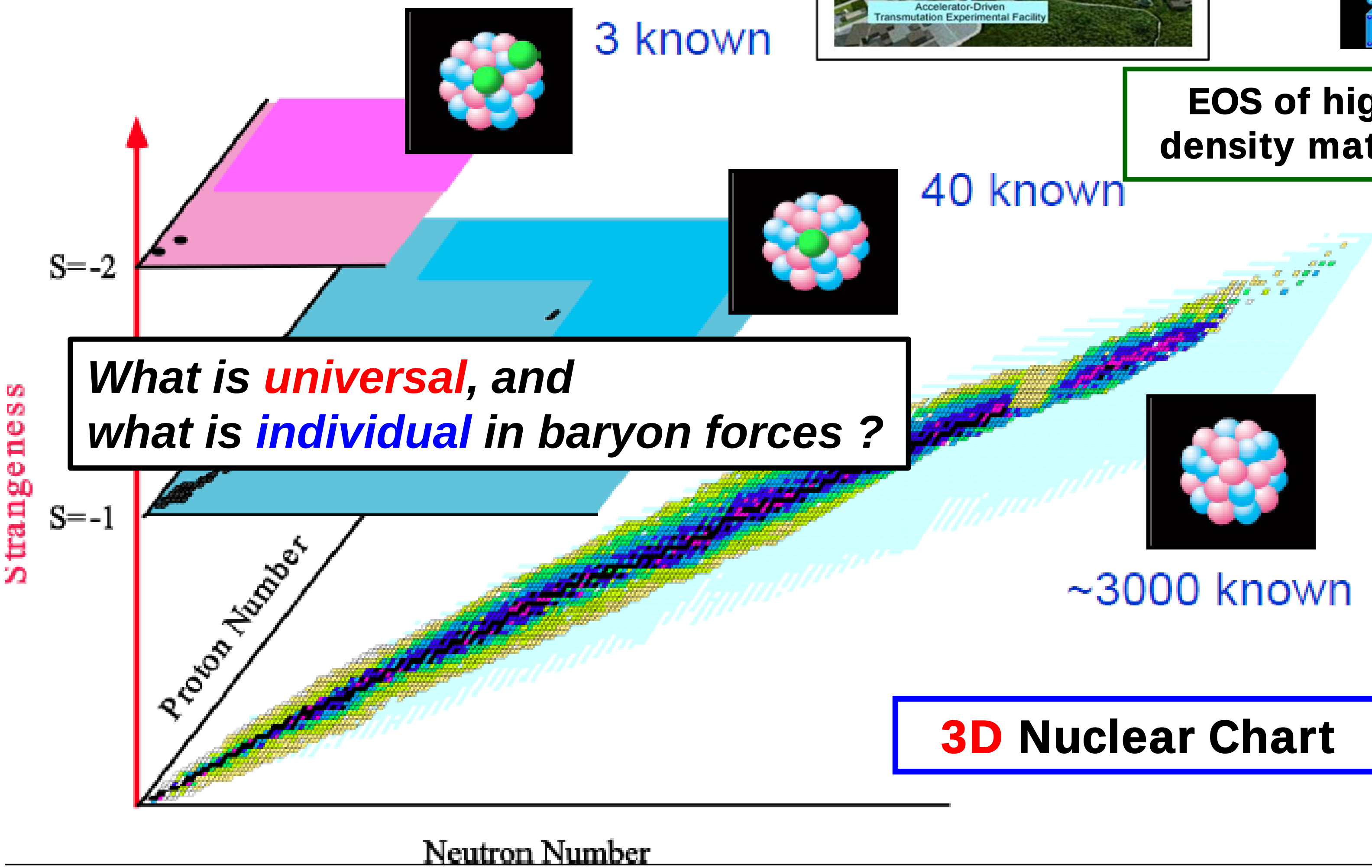
→ HyperNuclei



Neutron Star



EOS of high density matter



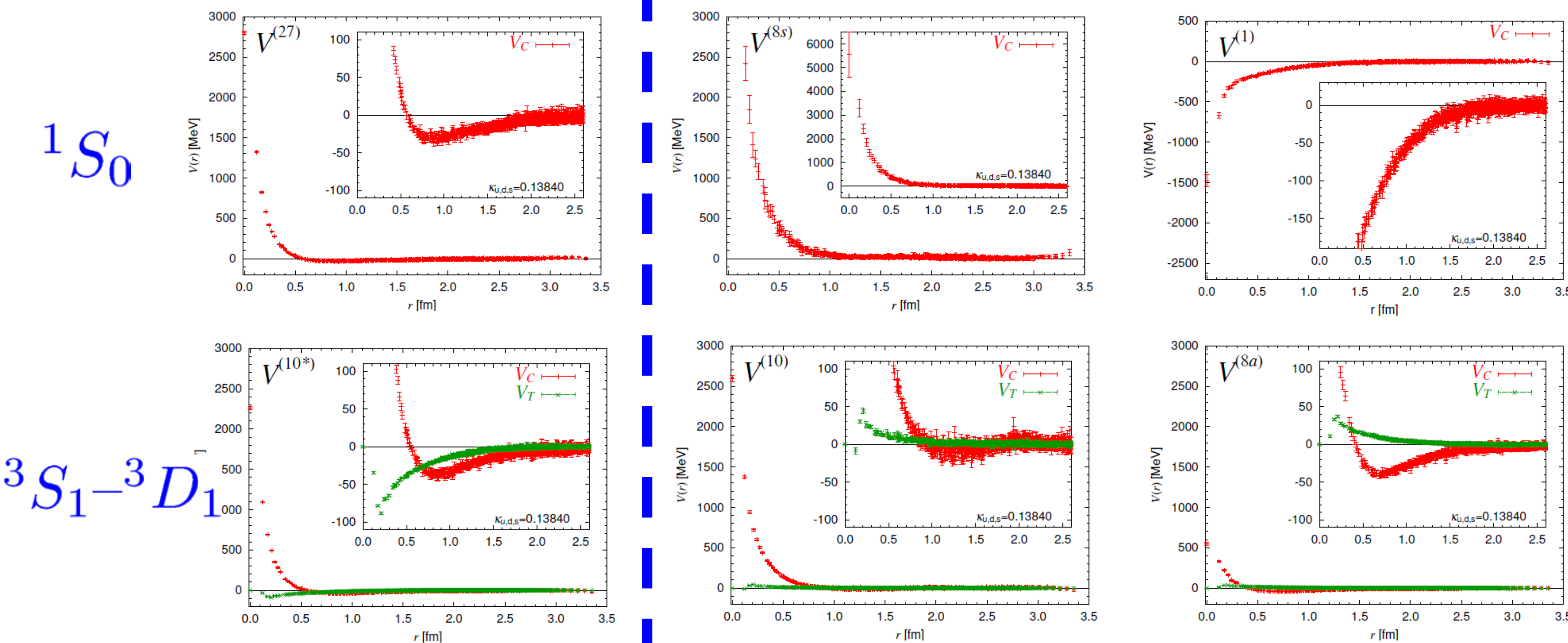
What is universal, and what is individual in baryon forces ?

3D Nuclear Chart

SU(3) study
$m_u = m_d = m_s$

Hyperon forces

a=0.12fm, L=3.9fm,
m(PS)= 0.47-1.2GeV



27,10*:
Same as NN

8s,10:
strong repulsive core

1s: deep attractive pocket
8a: weak repulsive core

Repulsive core
← Pauli principle !

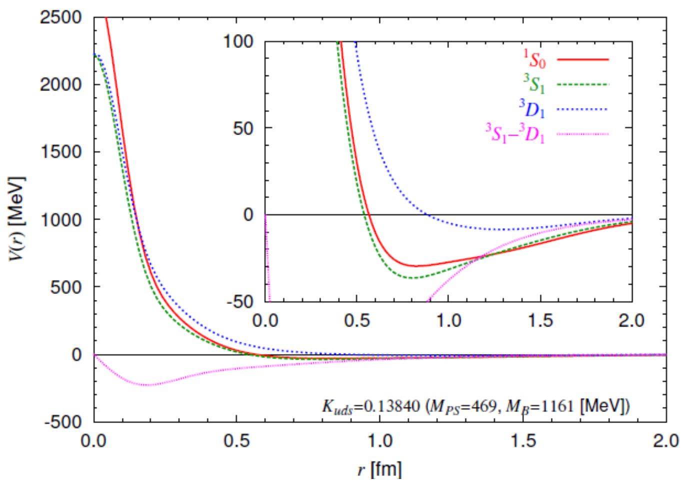
M.Oka et al., NPA464(1987)700

T.Inoue et al. (HAL QCD Coll.), NPA881(2012)28

Also seen in SU(2)c , Takahashi et al.,, PRD82(2010)094506
Charmonium-N, Kawanai-Sasaki, PRD82(2010)091501
Meson-baryon, Y.Ikeda et al., arXiv:1111.2663

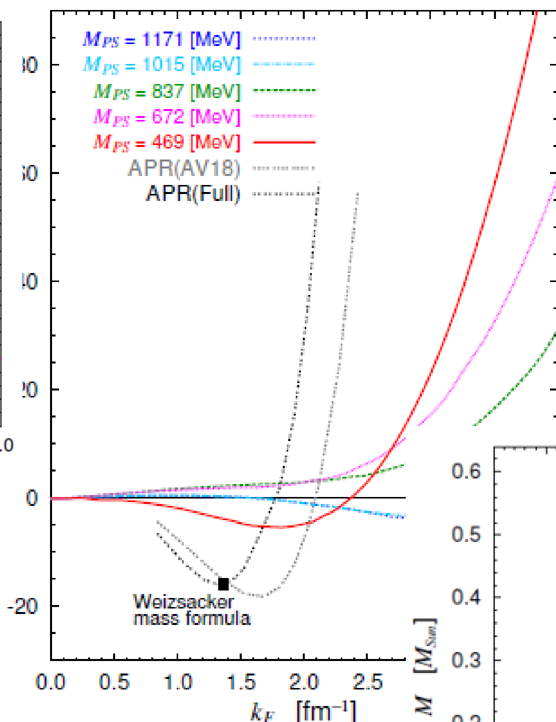
From QCD to Neutron Star

QCD → (**Lat QCD**) → **Lat NN forces** → (**BHF**) → **EoS** → (**TOV eq.**) → **Neutron Star**

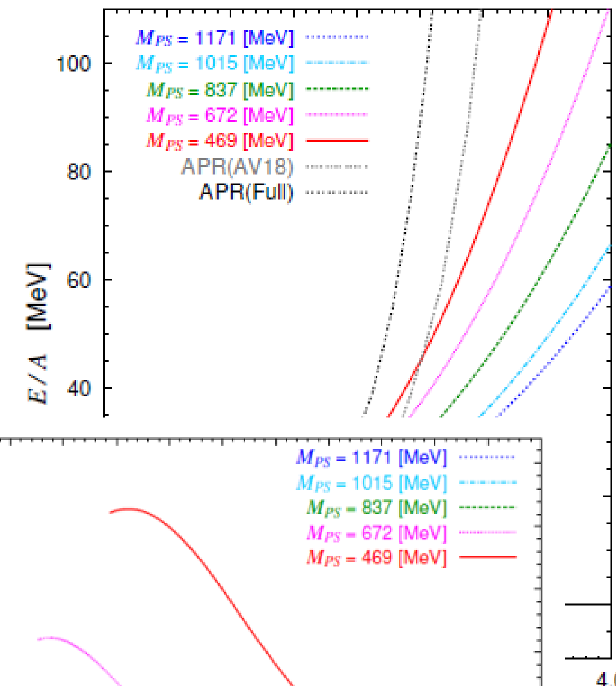


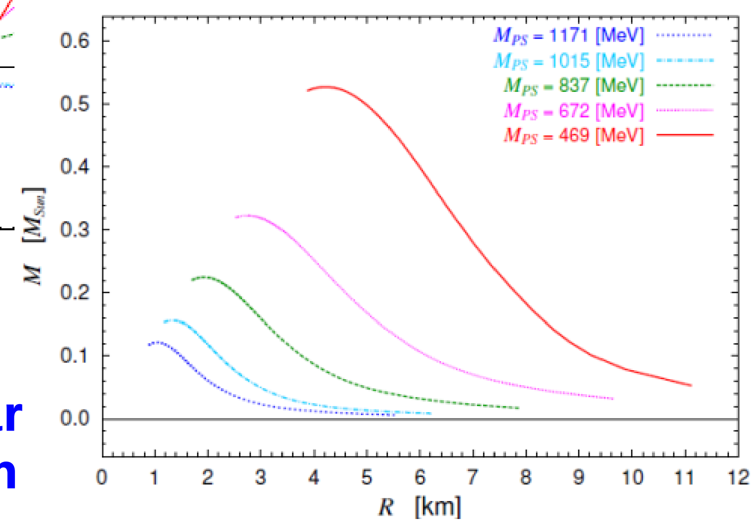
SU(3) study
m(PS)=0.47GeV

Sym. Nuclear matter



Neutron matter



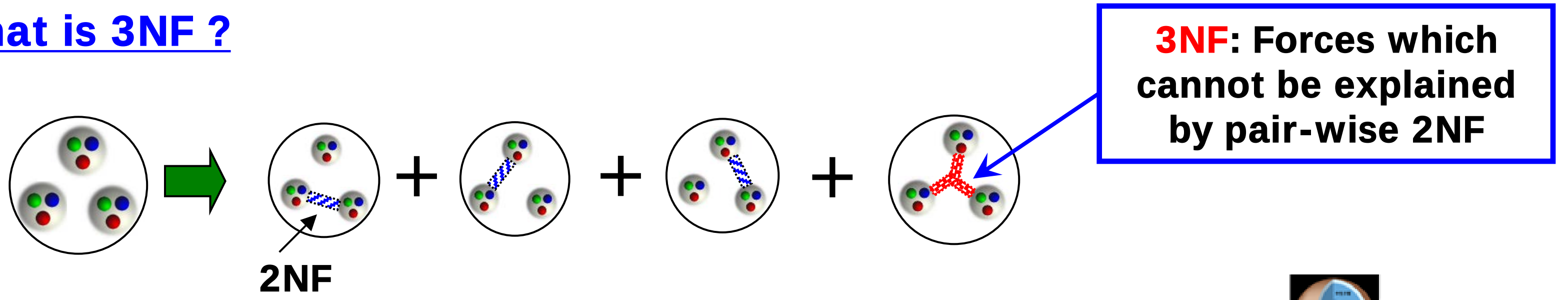


Neutron Star M-R relation

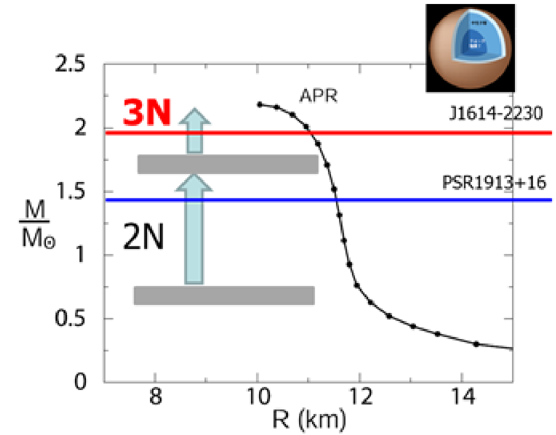
T.Inoue et al., PRL111(2013)112503

Three-nucleon forces (3NF)

What is 3NF ?



- 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*

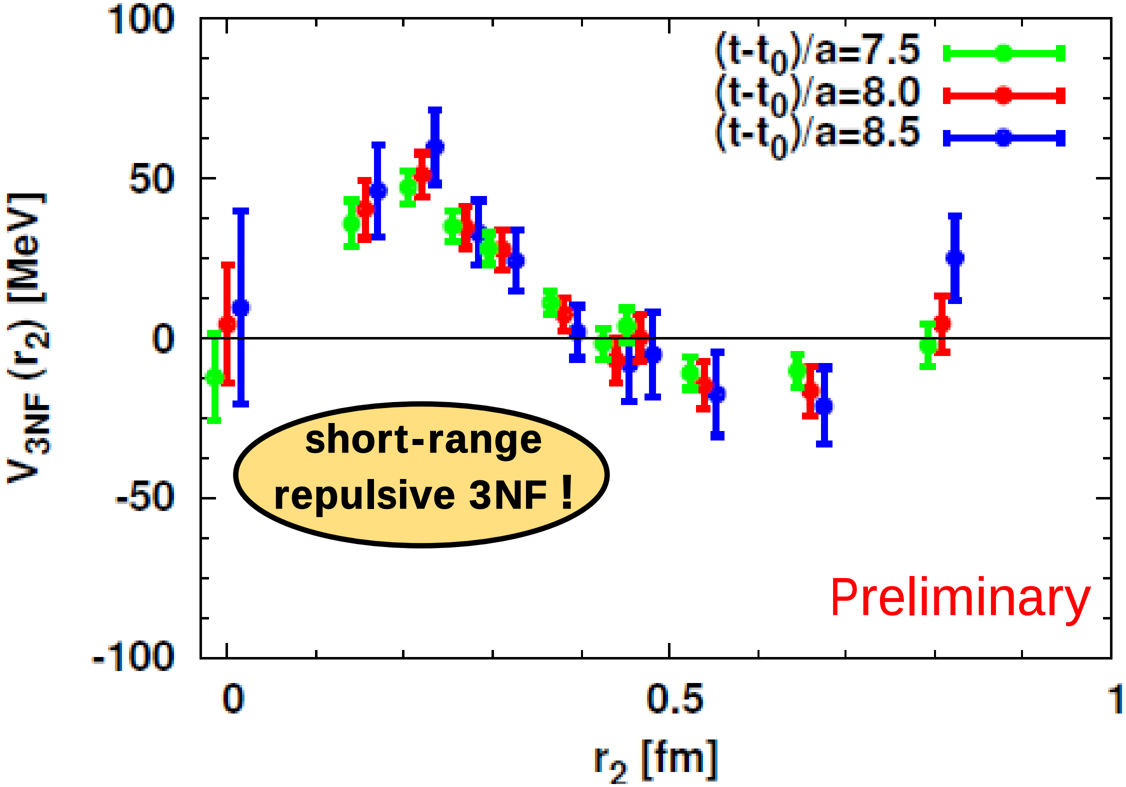
←→ *Nucleosynthesis*

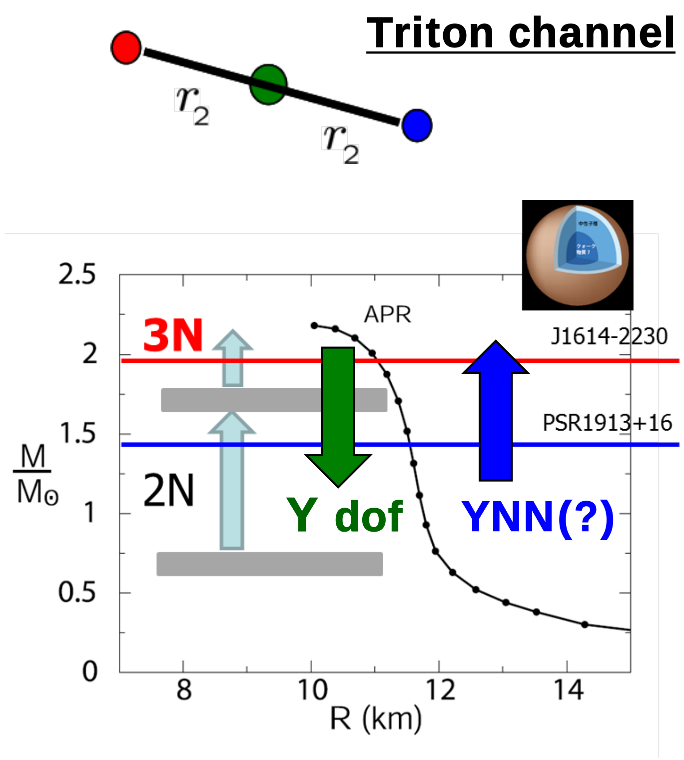
[RIBF-exp @ RIKEN]

3N-forces (3NF) on the lattice

T.D. et al. (HAL QCD Coll.) PTP127(2012)723

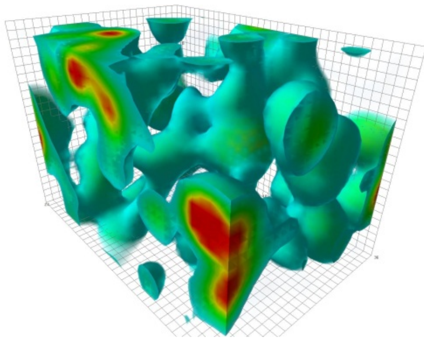
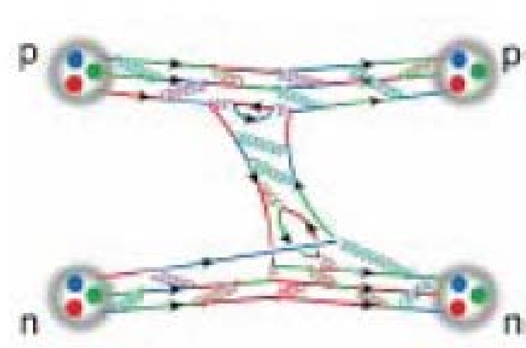
+ t-dep method updates etc.

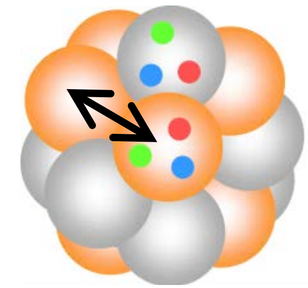




Nf=2 clover (CP-PACS), 1/a=1.27GeV,
L=2.5fm, m_π=1.1GeV, m_N=2.1GeV

How about
Thee-baryon forces w/ Hyperons ?



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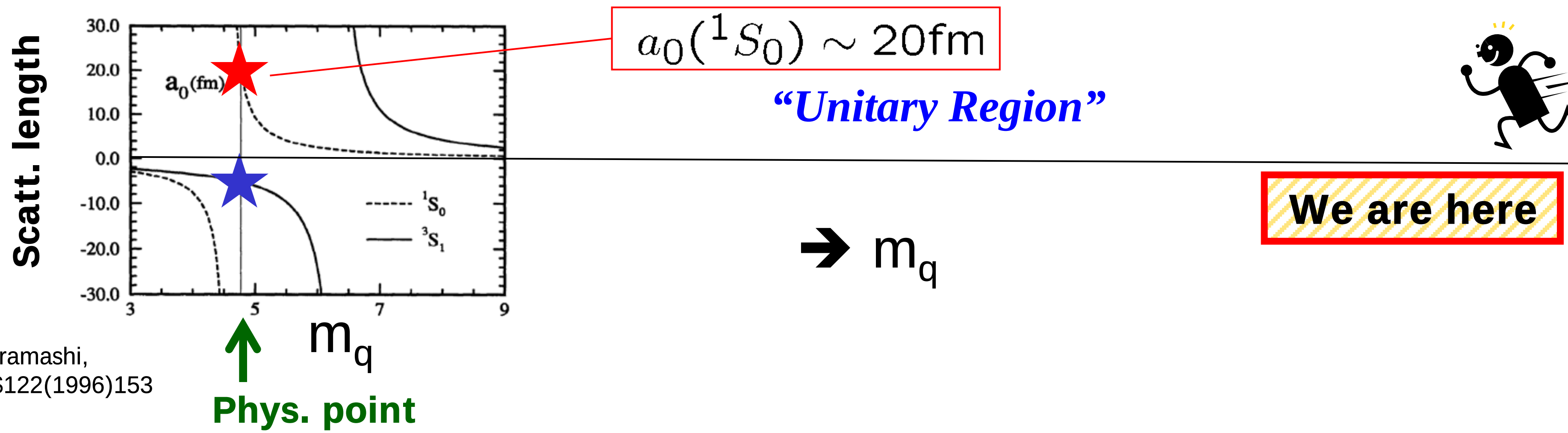
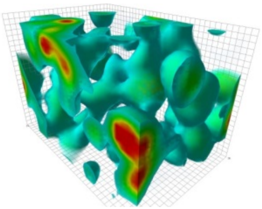
Towards realistic potential by the K computer

- **Physical mass point**, **Infinite V limit**, **continuum limit**
  - Physical mπ crucial for OPEP, chiral extrapolation won't work



Y.Kuramashi, PTPS122(1996)153

  - QCD vacuum generation at mπ = 140MeV, L=~9fm @ K



➔ **Challenge in the "measurement": S/N issue**

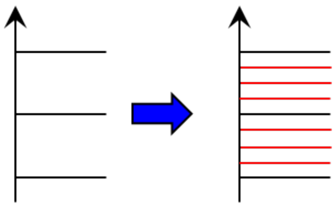
Challenge and Breakthrough in S/N issue

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

- S/N issue
  - **Traditional Lat calc ➔ G.S. saturation (or similar) is necessary**
  - **S/N gets worse** for larger mass number A & light quark mass & $t \to \infty$

$$S/N \sim \exp[-\mathbf{A} \times (\mathbf{m_N} - \mathbf{3/2m_\pi}) \times \mathbf{t}]$$

Larger V ➔ larger spectral density ➔ larger t



- Our solution: time-dependent HAL method
  - Extract the signal from excited states

E-indep of potential U(r,r') ➔ *(excited) scatt states share the same U(r,r')*

They are ***not contaminations, but signals***

  - Schrodinger eq: time-independent ➔ time-dependent
  - **Ground state saturation is NOT necessary !**

Recent Breakthrough in Algorithm

TD, M.Endres, CPC184(2013)117

- Enormous computational cost
  - Because of Wick contractions (permutation) x color/spinor contractions

$$\sim [(\tfrac{3}{2}A)!]^2 \text{ x } \sim 6^A \cdot 4^A$$

(color) (spinor)

  - **[Unified contraction algorithm]**
    - **Consider both contractions in a unified index space**
    - ➔ huge redundancies can be eliminated systematically
    - **Significant improvement**

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

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

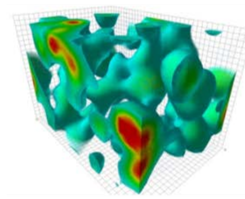
- Software development in K-computer
  - Extensive refactoring of the code with various tuning
  - 2BF: ~ x10-x100
  - 3NF: ~ x1000

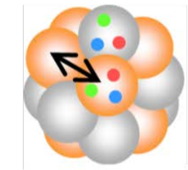
speedup

Prospects: challenges in post-K era

- **Physical mass point**, **Infinite V limit**, **continuum limit**
  - (how much precision can we achieve for deuteron B.E. ?)
- Three-body forces (3BF)
  - Generalized 3BF w/ Hyperons
  - Spacial config-dep, spin/flavor-dep
- Physical quantities other than phase shift & B.E.
    - e.g., matrix elements
- Chiral fermion in Lat QCD
  - ←→ Wilson fermion on "K" does not respect chiral-sym
- (Finite density on Lattice)
  - Sign problem

Summary

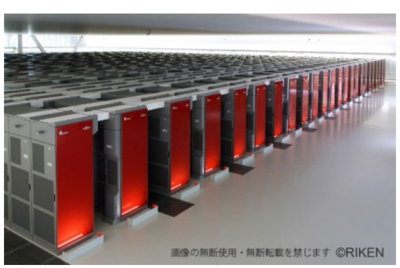




- Nuclear (Baryon) Forces by 1st principle Lat calc
  - Bridging different worlds:
    Particle Physics / Nuclear Physics / Astrophysics

- Lattice QCD results for NN, **YN/YY**, NNN, etc.
  - Intriguing physics even at heavy quark masses

- **Toward** physical quark mass point:
  - Breakthroughs in S/N issue & Comput. cost issue



Gauge confs in generation at m_π = 140MeV, L=9fm

➔ **Nuclear Physics on the Lattice !**