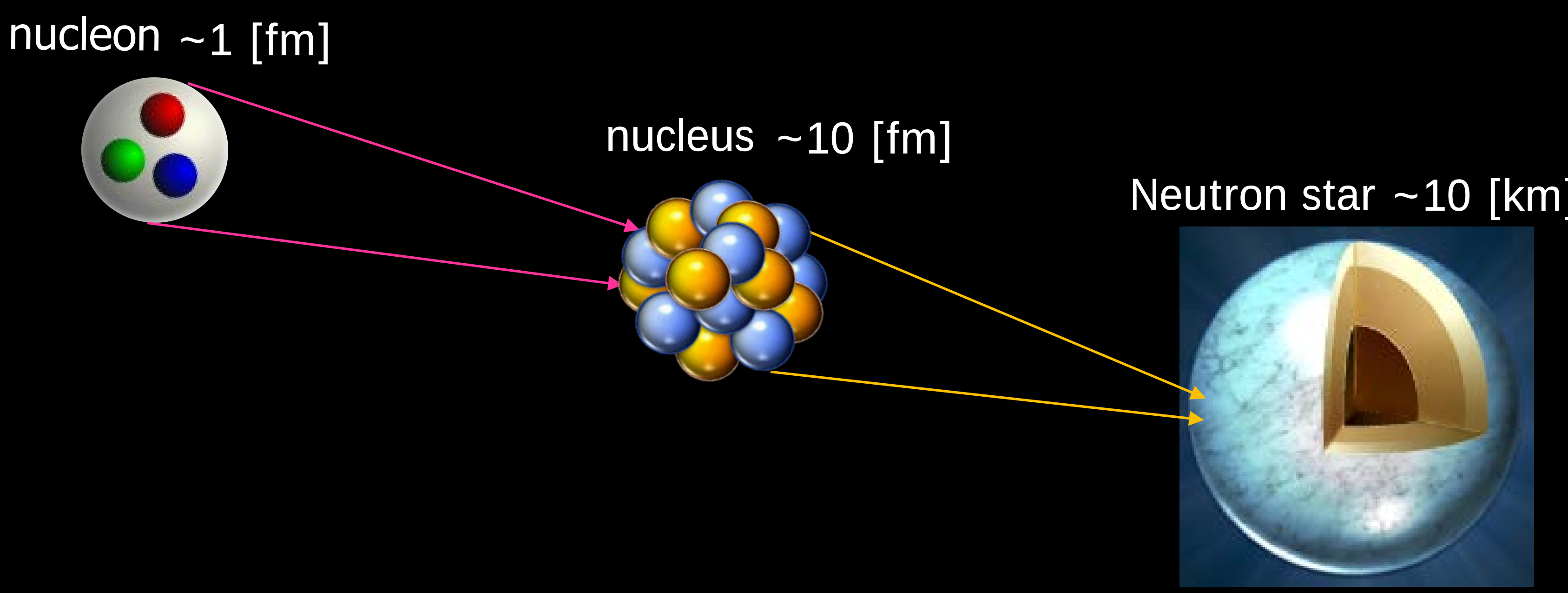
From QCD to Compact Stars



Advances and Perspectives in Computational Nuclear Physics
Hilton Waikoloa Village (Hawaii, Oct. 6, 2014)
Tetsuo Hatsuda (RIKEN)

Plan of this Talk

1. Introduction : phase structure of QCD
2. Baryon forces from LQCD

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

3. Nuclear & Neutron Matter from LQCD + BHF

   Inoue et al. [HAL QCD Coll.], PRL 111 (2013) 112503

4. Finite Nuclei from LQCD + BHF

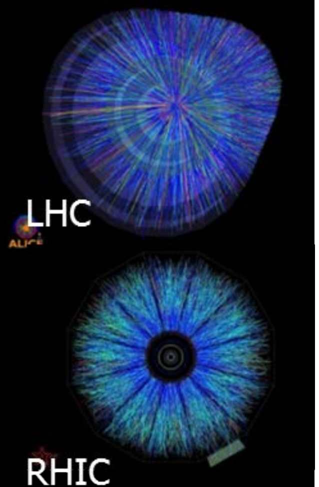
   Inoue et al. [HAL QCD Coll.], arXiv: 1408.4892

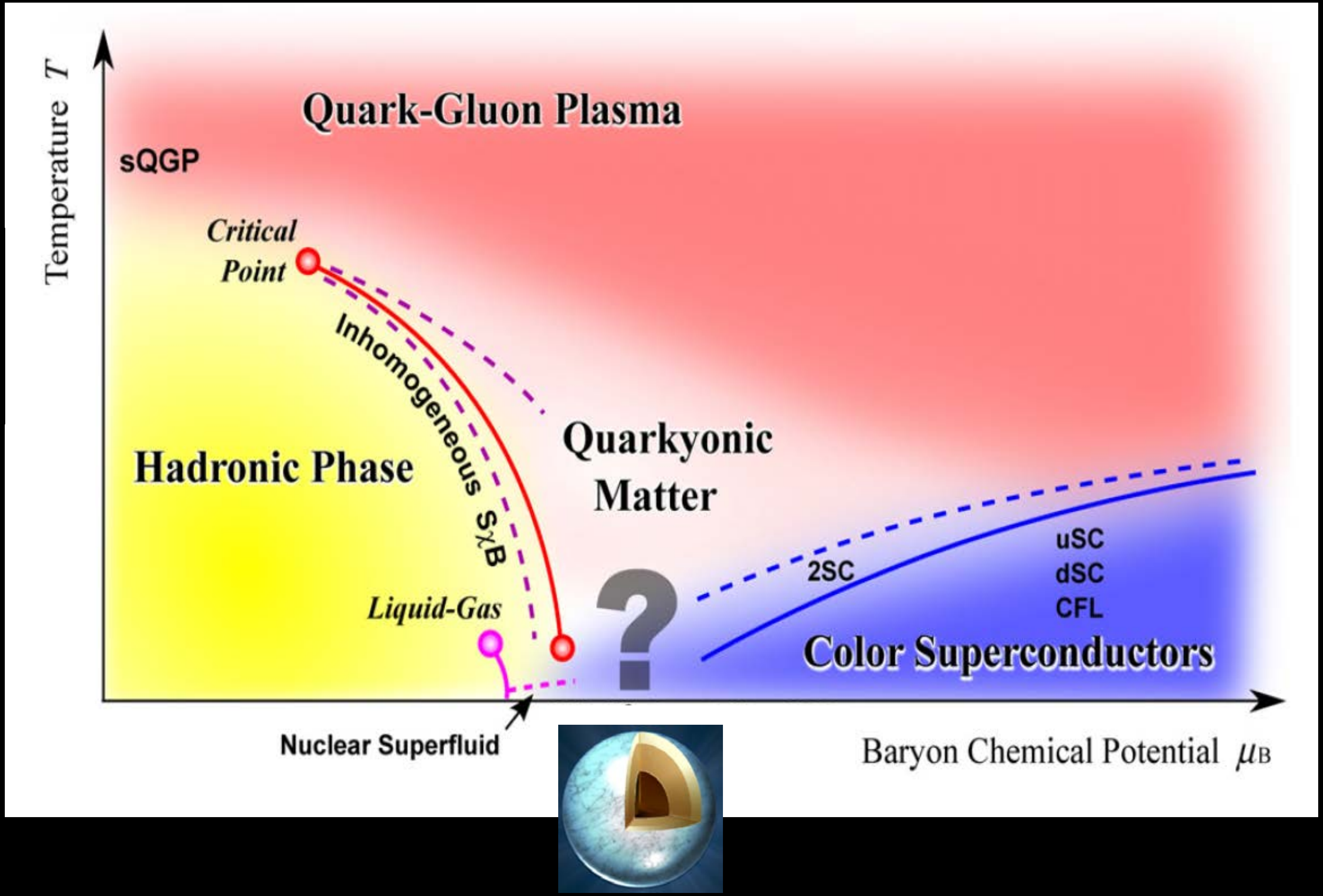
5. Summary

Exotic (strange and charmed) Hadrons (H , NΩ , T_{cc} , T_{cs} , Z_c etc)

⇒ Y. Ikeda (Oct.7, morning)

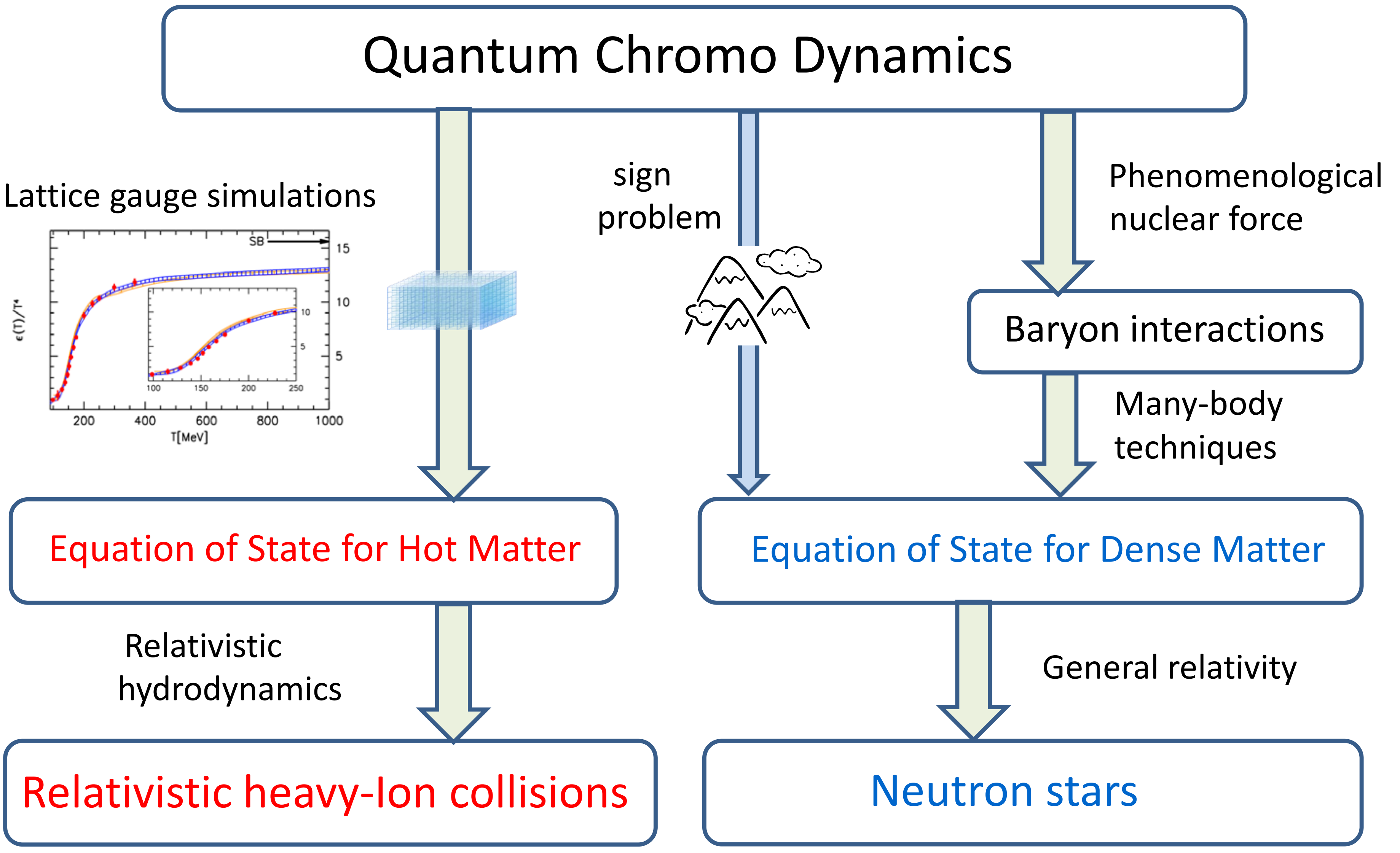
Possible QCD Phase Structure



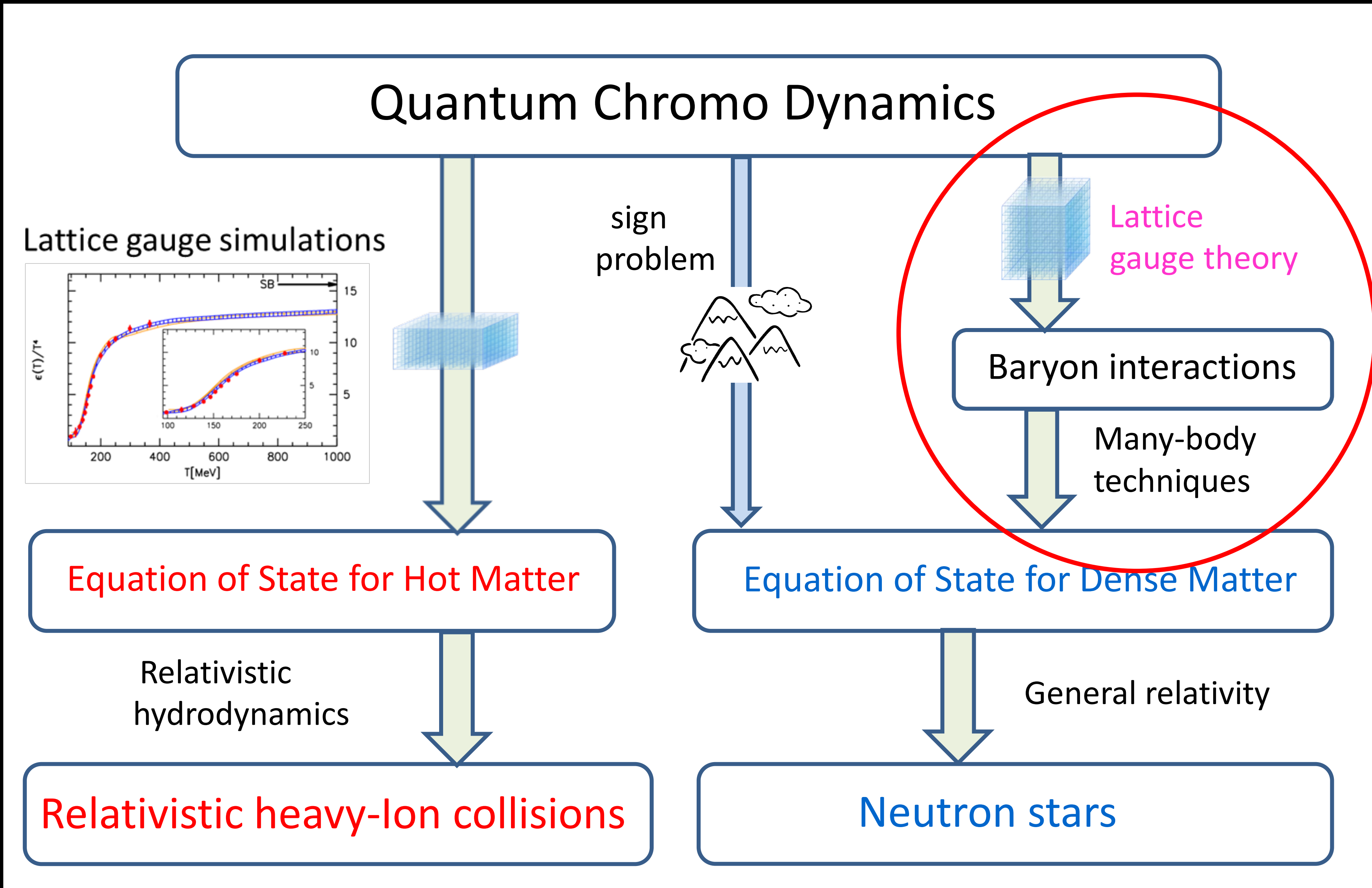


K. Fukushima and T. Hatsuda, "The Phase Diagram of Dense QCD"
Rep. Prog. Phys. 74 (2011) 014001

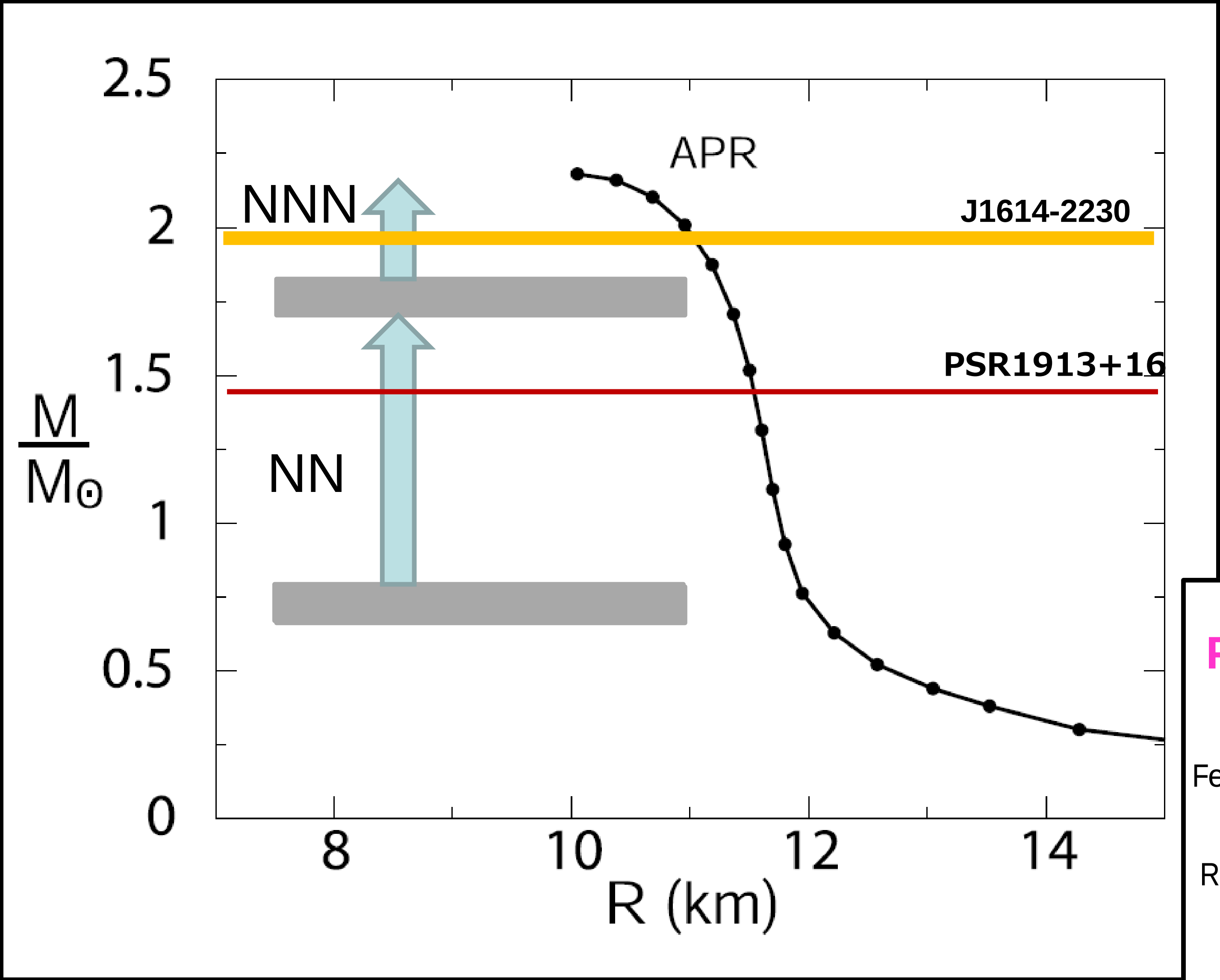
From QCD to Hot/Dense Matter

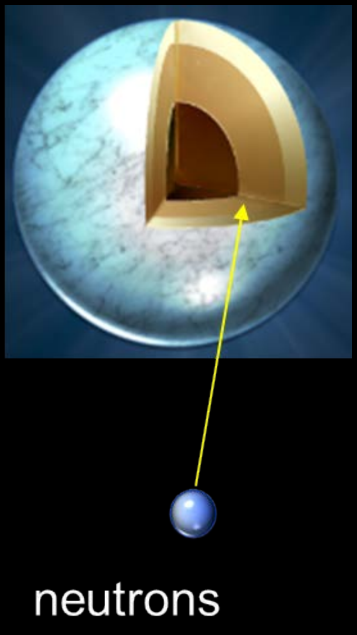


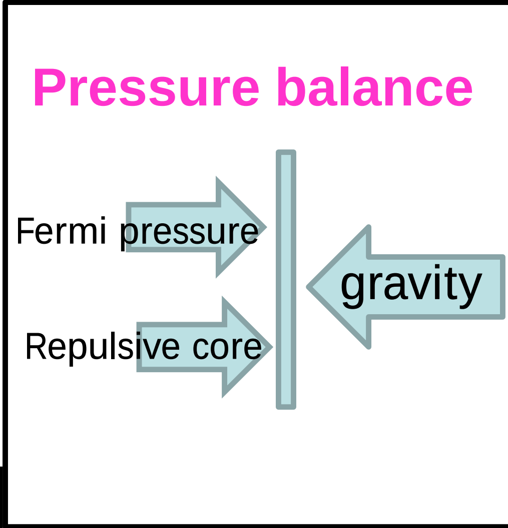
From QCD to Hot/Dense Matter



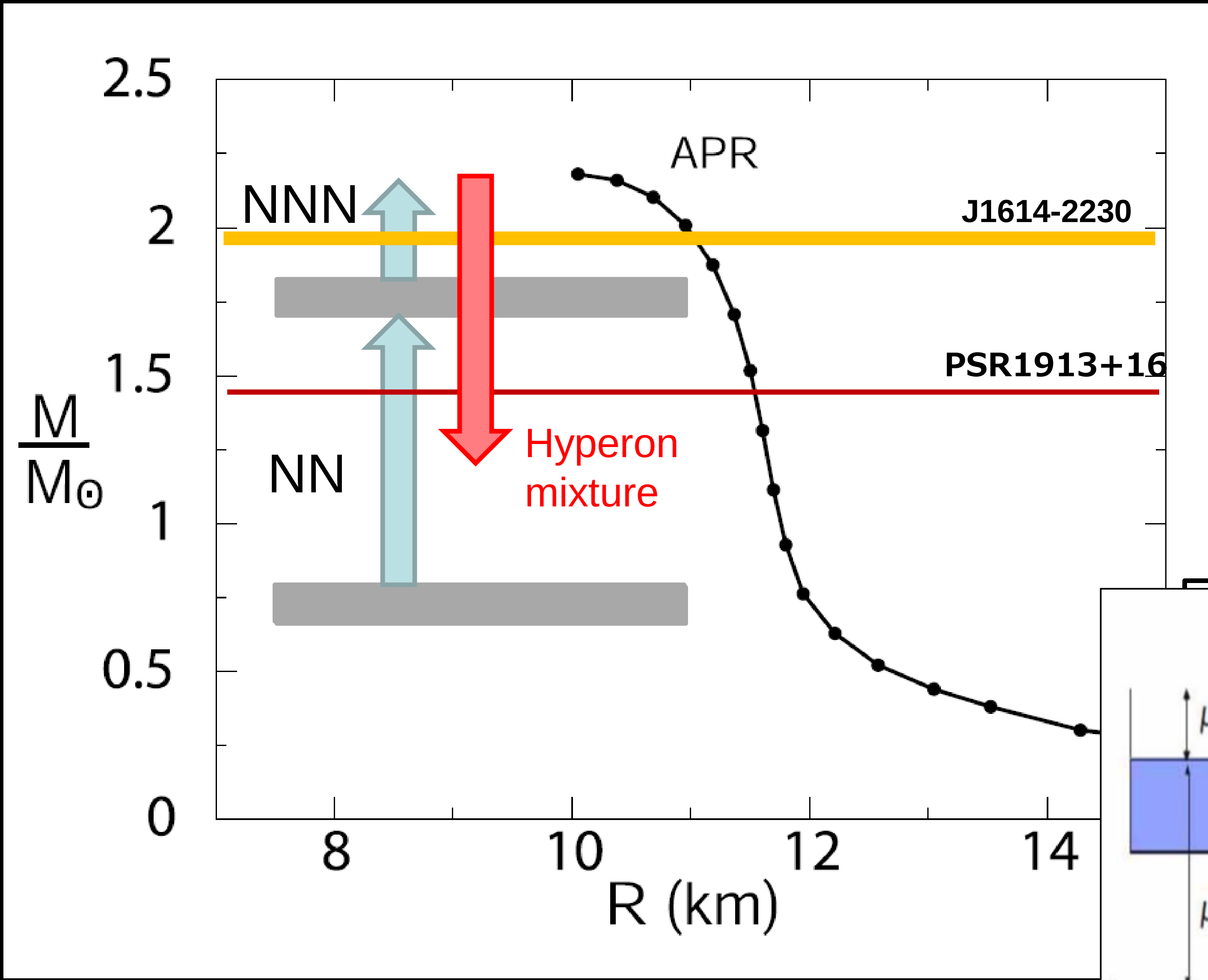
Mass-Radius relation of N☆ (nucleons only)

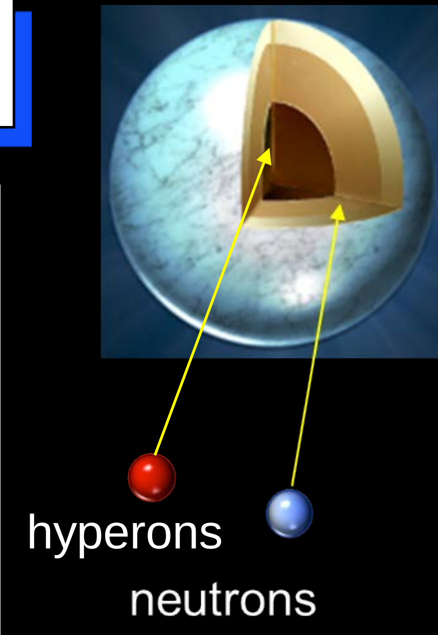


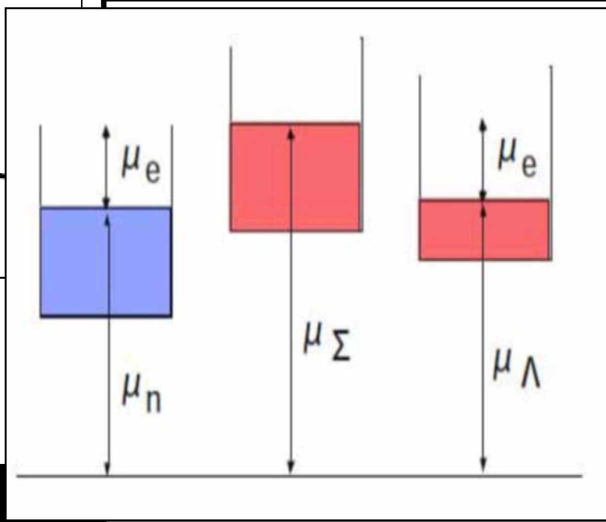




Hyperon Crisis (Takatsuka et al., 2002)







HPCI Program (FY2011-2015) Field 5: All Japan Computational Physics Collaboration

The Origin of Matter and the Universe

(particle physics – nuclear physics – astrophysics, 11 institutions)

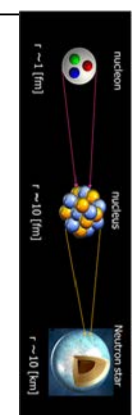
Lattice 2015 (July)
Quark Matter 2015 (Oct.)

Project 1: Baryon-Baryon interaction from lattice QCD

Project 2: Nuclear quantum many-body calculation

Project 3: Supernova explosion and black-hole formation

Project 4: First stars and galaxies



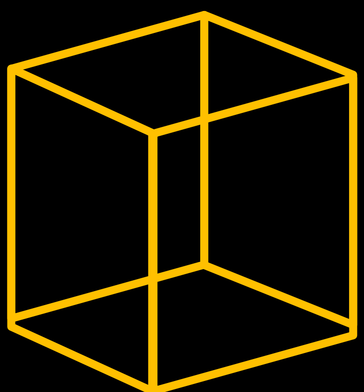
Present un-physical point simulation
for single and multi-baryons

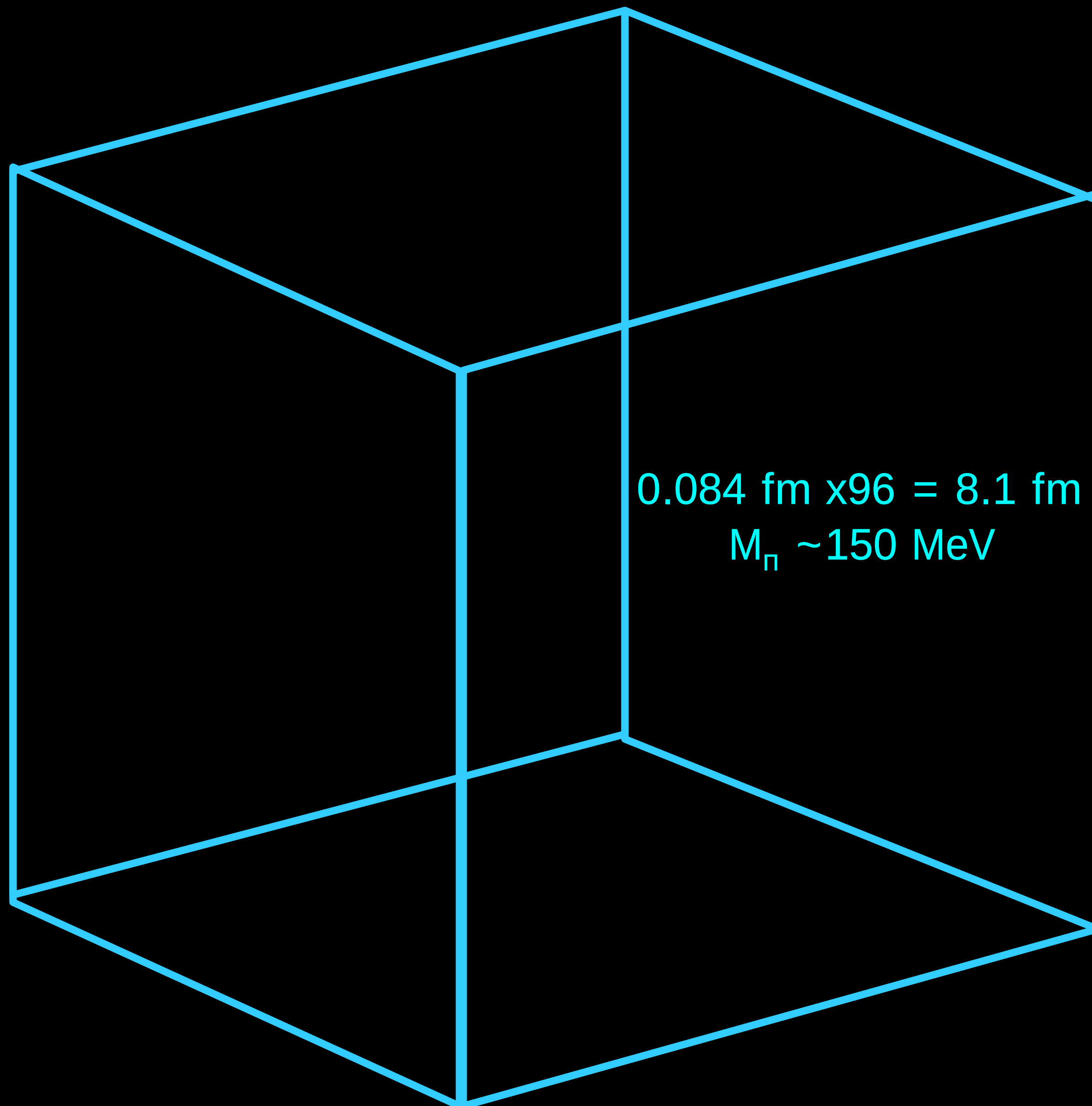
On-going physical point simulation
for single and multi-baryons in K

NEXT YEAR'S TALK
Stay Tuned !!

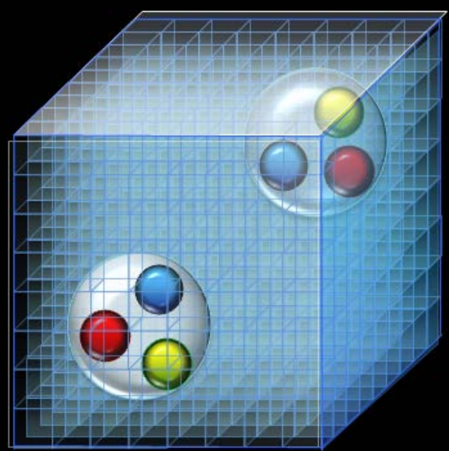
TODAY'S TALK

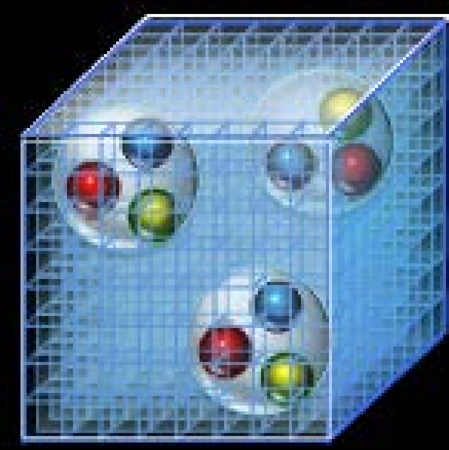
0.121 fm x32 = 3.9 fm
m_π=350-1200 MeV





Baryon Forces from LQCD



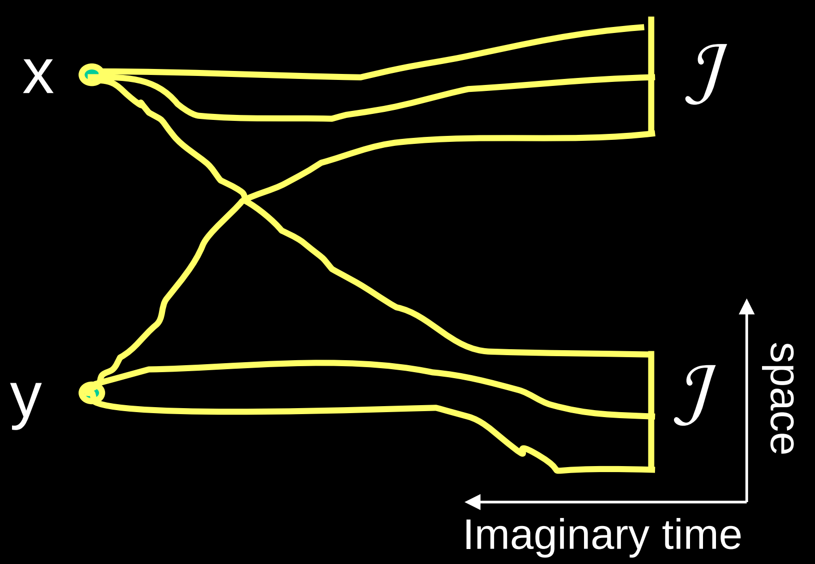


Hadrons to Atomic nuclei HAL from Lattice QCD

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

Review: “Lattice QCD Approach to Nuclear Physics”
HAL QCD Collaboration, Prog. Theor. Exp. Phys. 2012 (2012) 01A105

Hadronic correlations in LQCD



$$\langle N_1(\mathbf{x},t) N_2(\mathbf{y},t) \mathcal{J}_1^\dagger(0) \mathcal{J}_2^\dagger(0) \rangle$$
$$= \sum_n \langle 0 | N_1(\mathbf{x}) N_2(\mathbf{y}) | n \rangle a_n e^{-E_n t}$$
$$\xrightarrow{t>t^*} \phi(\mathbf{r},t) = \sum_{n<n^*} b_n \phi_n(\mathbf{r}) e^{-E_n t}$$

Finite Volume Method

$E_n(L)$ → phase shift

Luescher, Nucl. Phys. B354 (1991) 531

HAL QCD Method

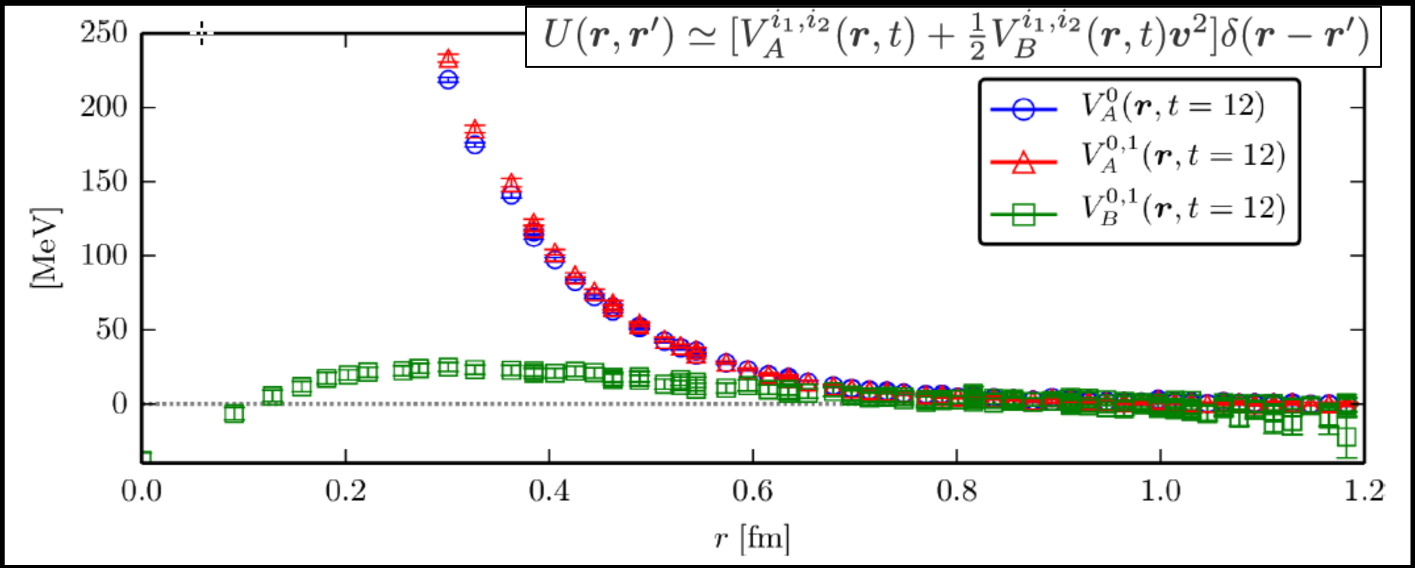
$\phi(r,t)$ → kernel → phase shift

T=V+GVT

Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001

Ishii et al. [HAL QCD Coll.], PLB 712 (2012) 437

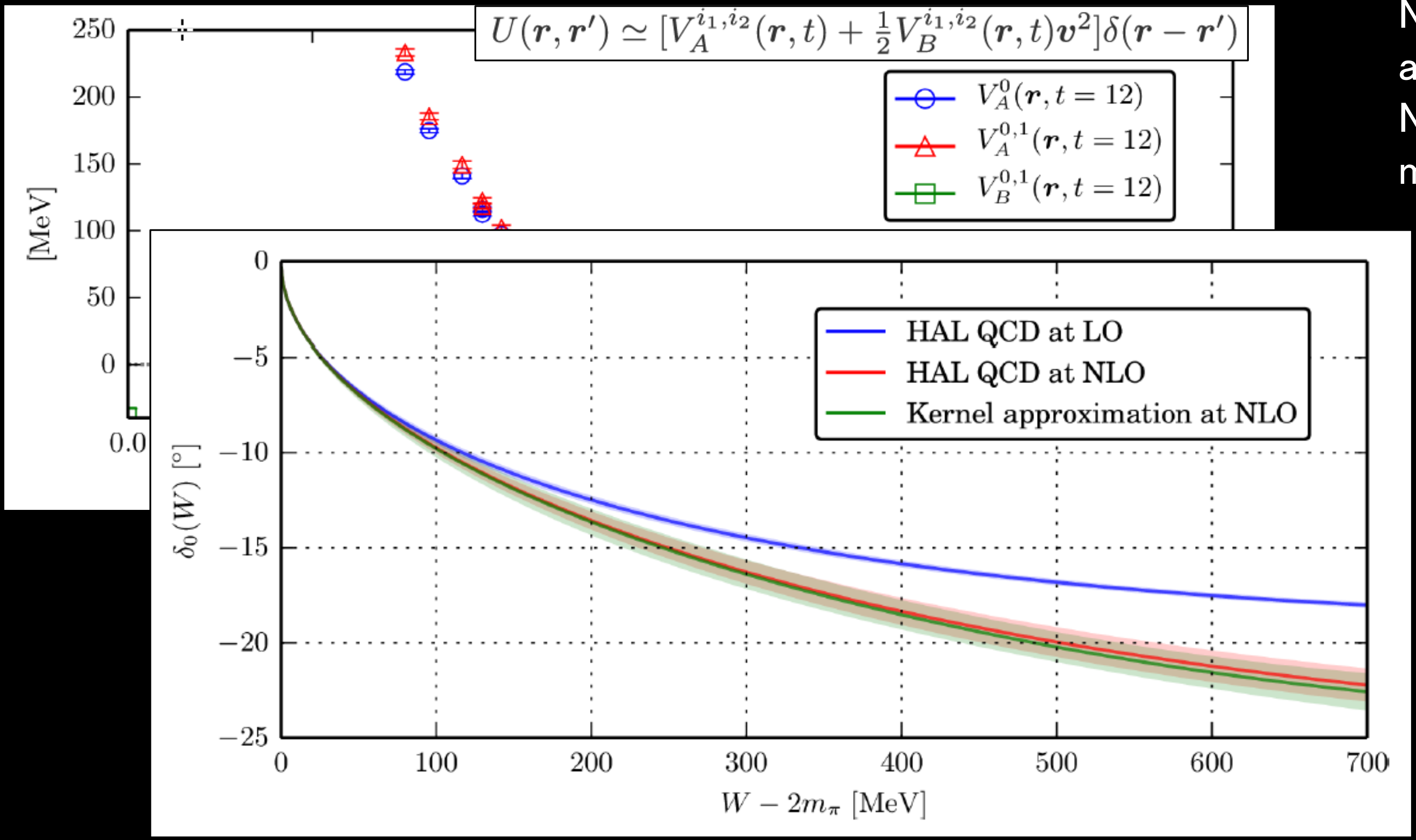
Benchmark test : FV Method vs. HAL QCD Method



$N_f = 2+1$
$a = 0.091$ fm
$N_s^3 x N_t = 32^3 x 64$
$m_\pi = 700$ MeV

B. Charron, PhD thesis, Univ. Tokyo (2014)
See also, Kurth, Ishii, Doi, Aoki & Hatsuda, JHEP 1312 (2013) 015

Benchmark test : FV Method vs. HAL QCD Method



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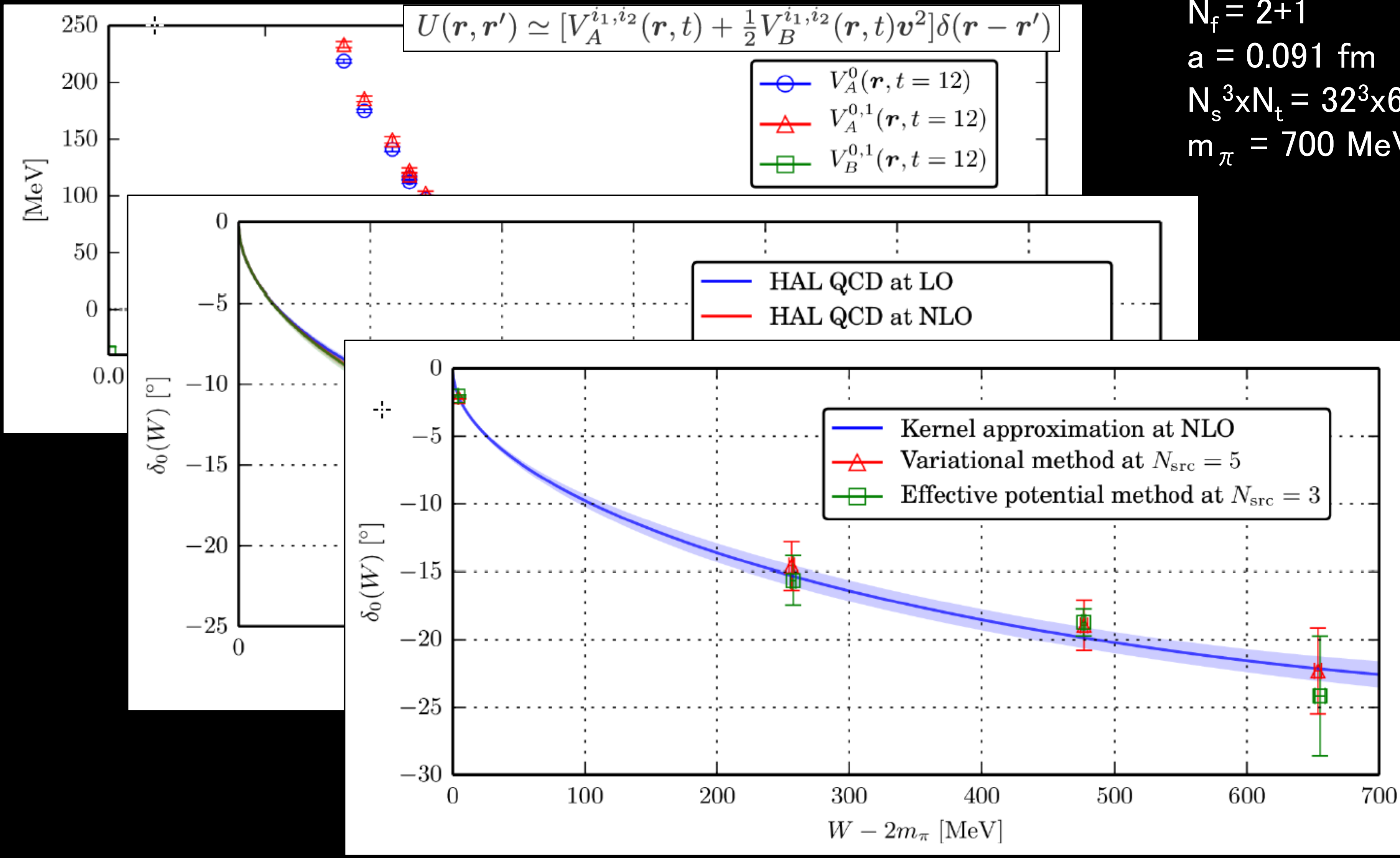

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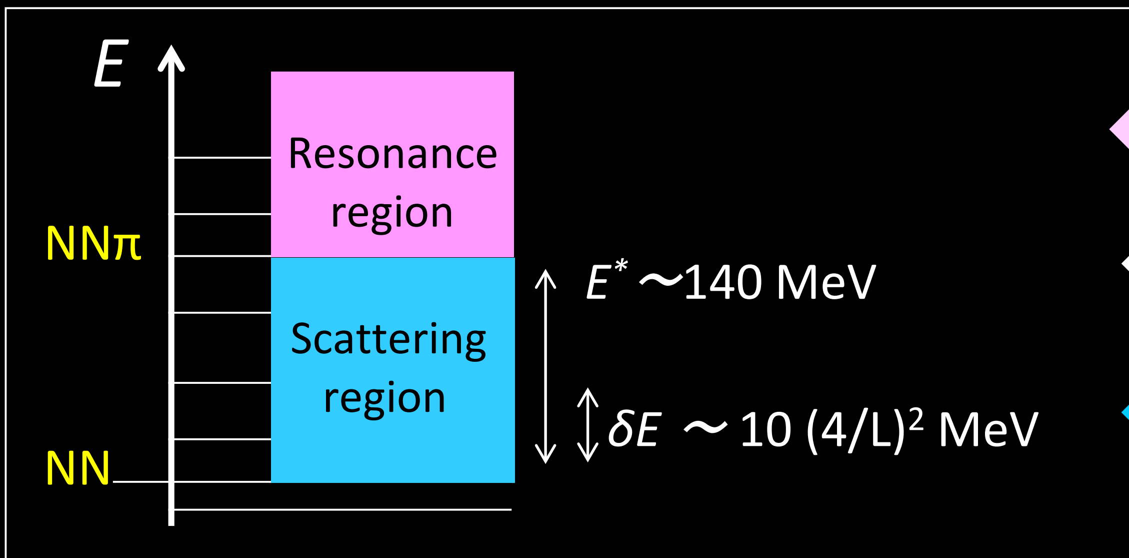
See also, Kurth, Ishii, Doi, Aoki & Hatsuda, JHEP 1312 (2013) 015

What about NN ?



$t < 1$ fm

$t^* \sim 1$ fm

$t > 20\,(L/4)^2$ fm

$$\left(\frac{\mathcal{S}}{\mathcal{N}}\right)_{NN} \sim \sqrt{N_{\rm gc}}\; e^{-2(m_N - 3m_\pi/2)t}$$

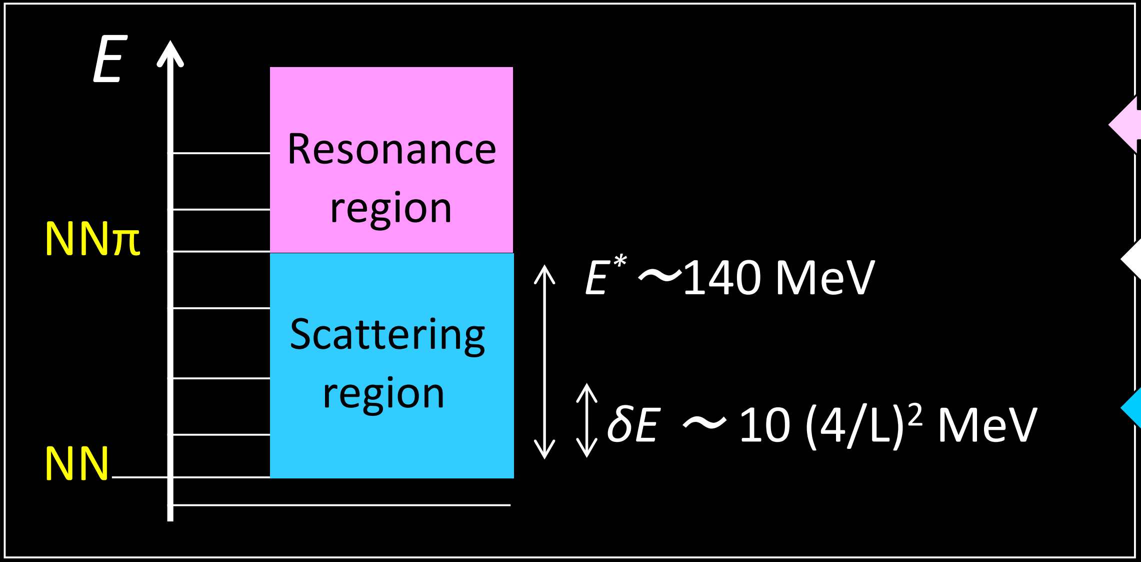
$$\left(\frac{\mathcal{S}}{\mathcal{N}}\right)_{\pi\pi} \sim \sqrt{N_{\rm gc}}$$

Finite Volume Method

- Large t and huge statistics are required for NN (not for ππ) for small m_π and large L

P. Lepage, TASI 1989 Lecture

What about NN ?



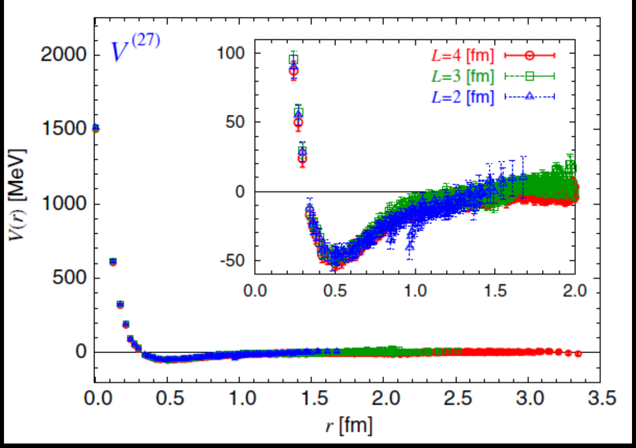
- $t < 1$ fm
- $t^* \sim 1$ fm
- $t > 20\,(L/4)^2$ fm

$$\left[\left(\frac{1}{2}\frac{\partial}{\partial t}\right)^2 - \nabla^2 + m_N^2\right]\phi(\mathbf{r},\mathbf{t}) = m_N \int U(\mathbf{r},\mathbf{r}')\phi(\mathbf{r}')d^3r'$$

HAL QCD Method

- All data for t > 1 fm are signals
- U(r,r') : non-local kernel
  E-independent, L-insensitive → observables

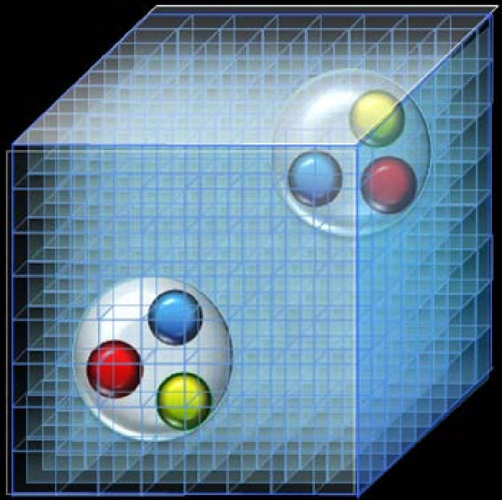
Ishii et al. [HAL QCD Coll.], PLB 712 (2012) 437



Lattice setup
to be used in the following analyses

3 degenerate flavors

Iwasaki gauge action + clover improved Wilson fermion

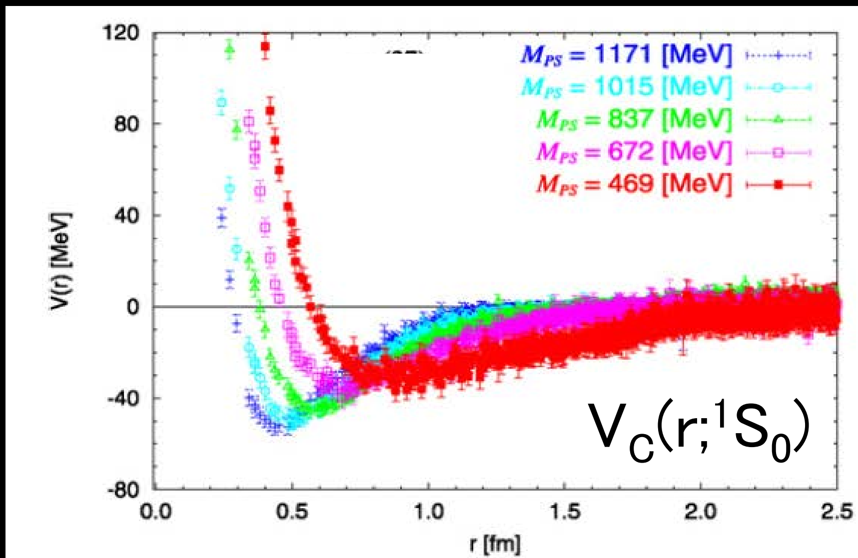


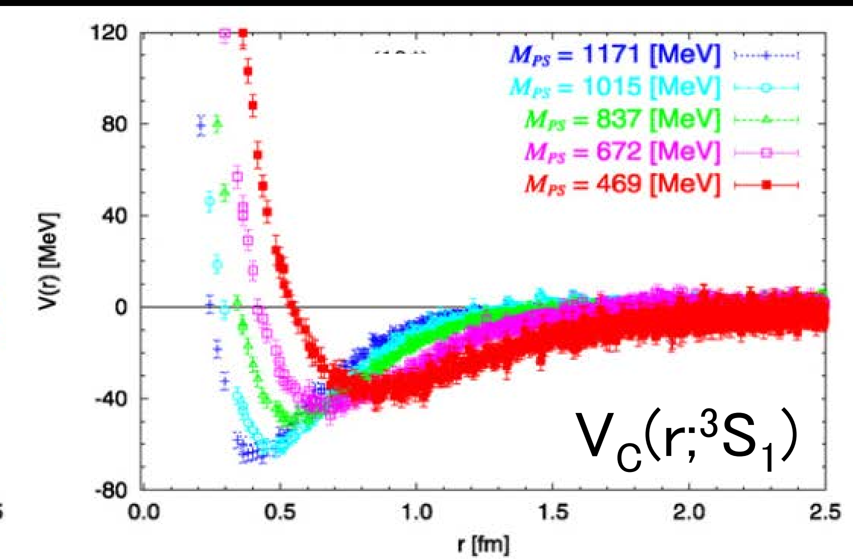
size	β	Csw	a [fm]	L [fm]
32^3 x 32	1.83	1.761	0.121(2)	3.87

K_uds	M_P.S. [MeV]	M_B⁸ [MeV]
0.13660	1170.9(7)	2274(2)
0.13710	1015.2(6)	2031(2)
0.13760	836.8(5)	1749(1)
0.13800	672.3(6)	1484(2)
0.13840	468.9(8)	1161(2)

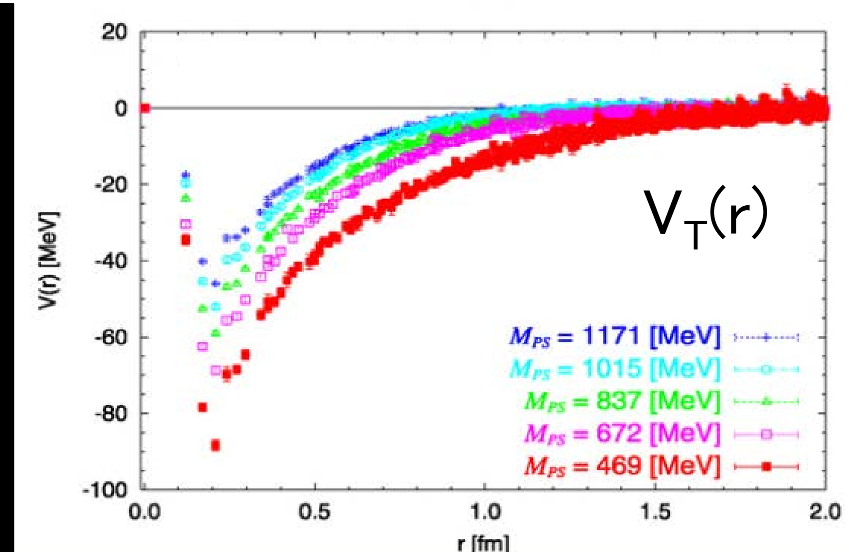
$$V(\vec{r},\nabla) = V_{\rm C}(r) + S_{12}V_{\rm T}(r) + \vec{\rm L}\cdot\vec{\rm S}\; V_{\rm LS}(r) + \{V_{\rm D}(r), \nabla^2\} + \cdots$$

LO LO NLO NNLO



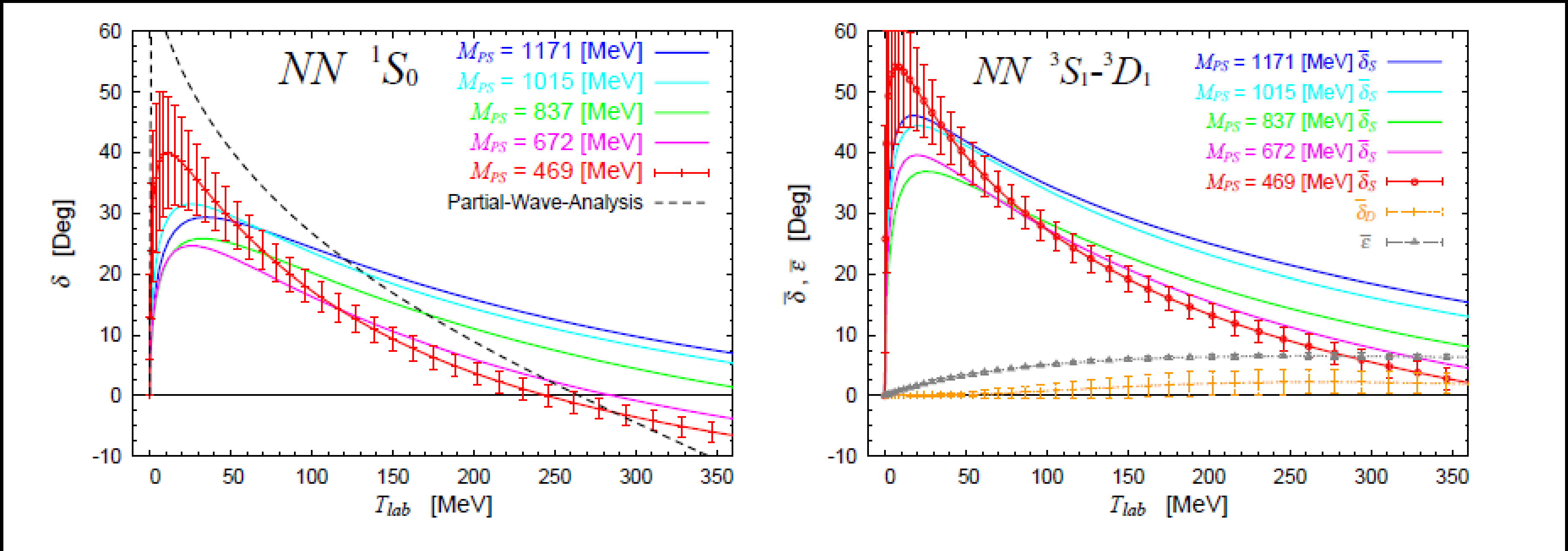


NN
Central & Tensor Forces
in 3-flavor QCD



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

NN phase shifts in 3-flavor QCD



Stronger attraction in the deuteron channel

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

BB Forces in 3-flavor QCD

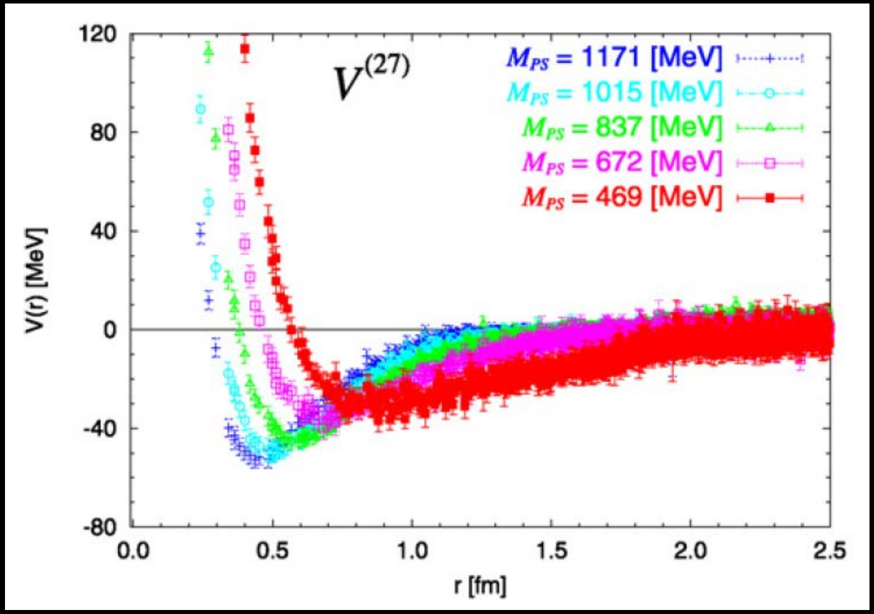
HAL QCD Coll.
Phys. Rev. Lett. 106 (2011) 162002
Nucl. Phys. A881 (2012) 28

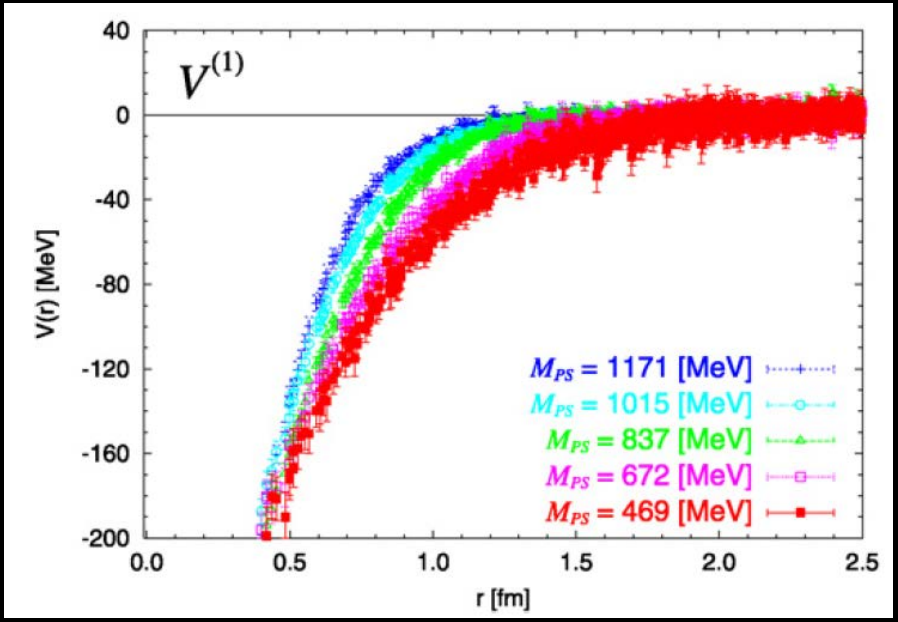
PP (uud-uud) channel

(partial) Pauli blocking

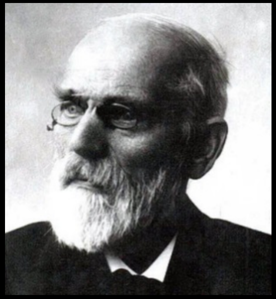
H (uds-uds) channel

No Pauli blocking





Pauli and van der Waarls
at work !

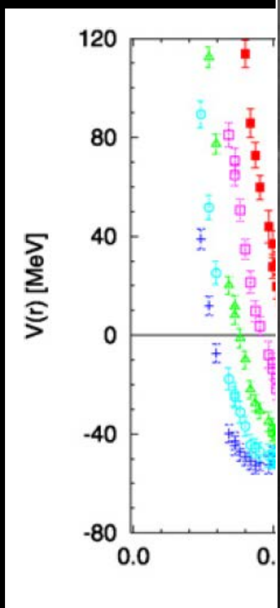


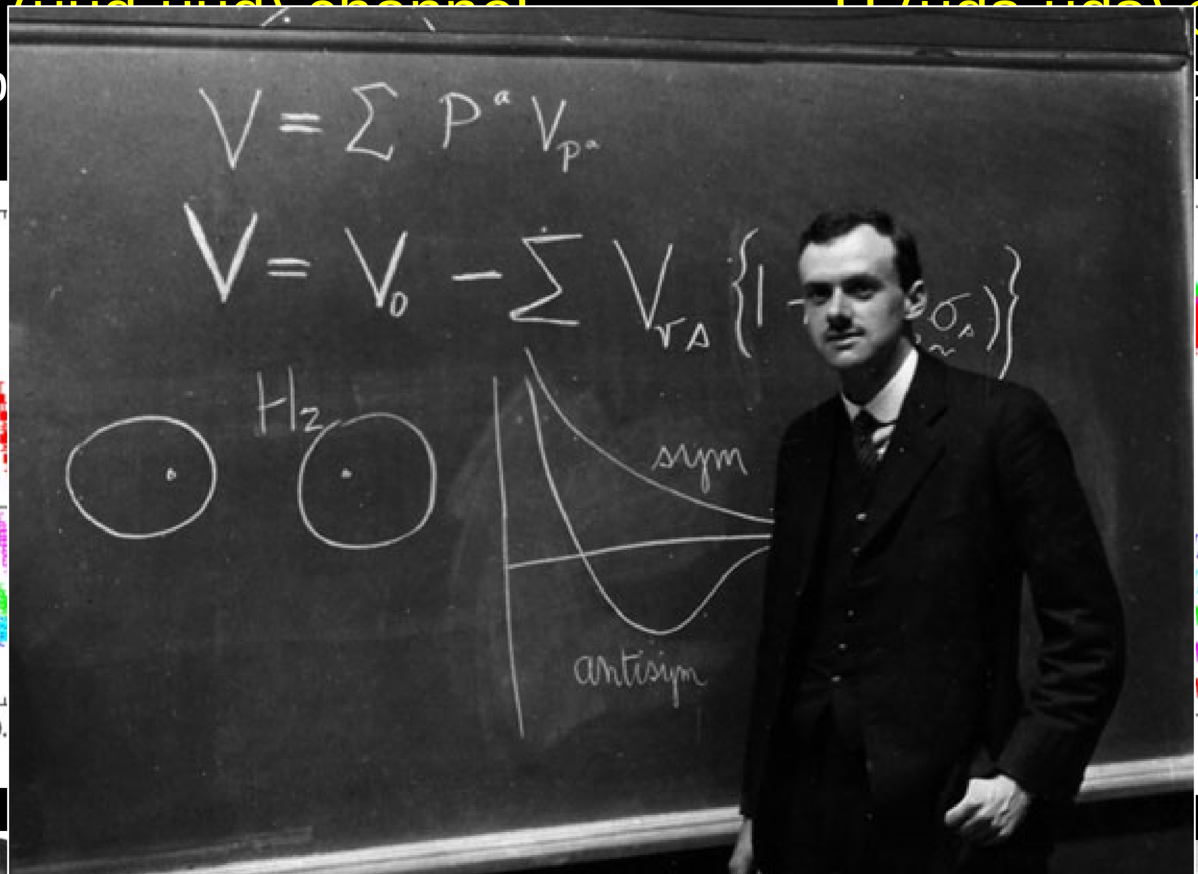
BB Forces in 3-flavor QCD

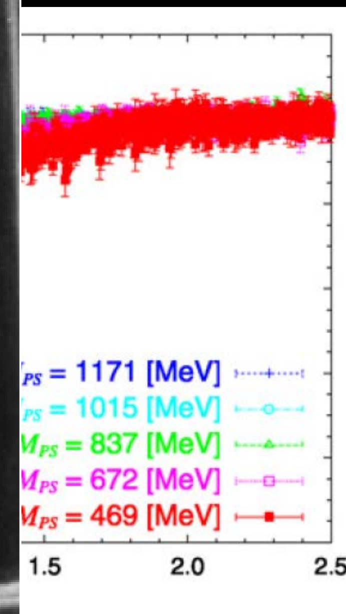
HAL QCD Coll.
Phys. Rev. Lett. 106 (2011) 162002
Nucl. Phys. A881 (2012) 28

PP ... channel

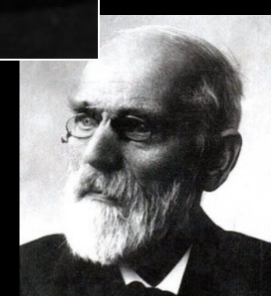
(p ... cking



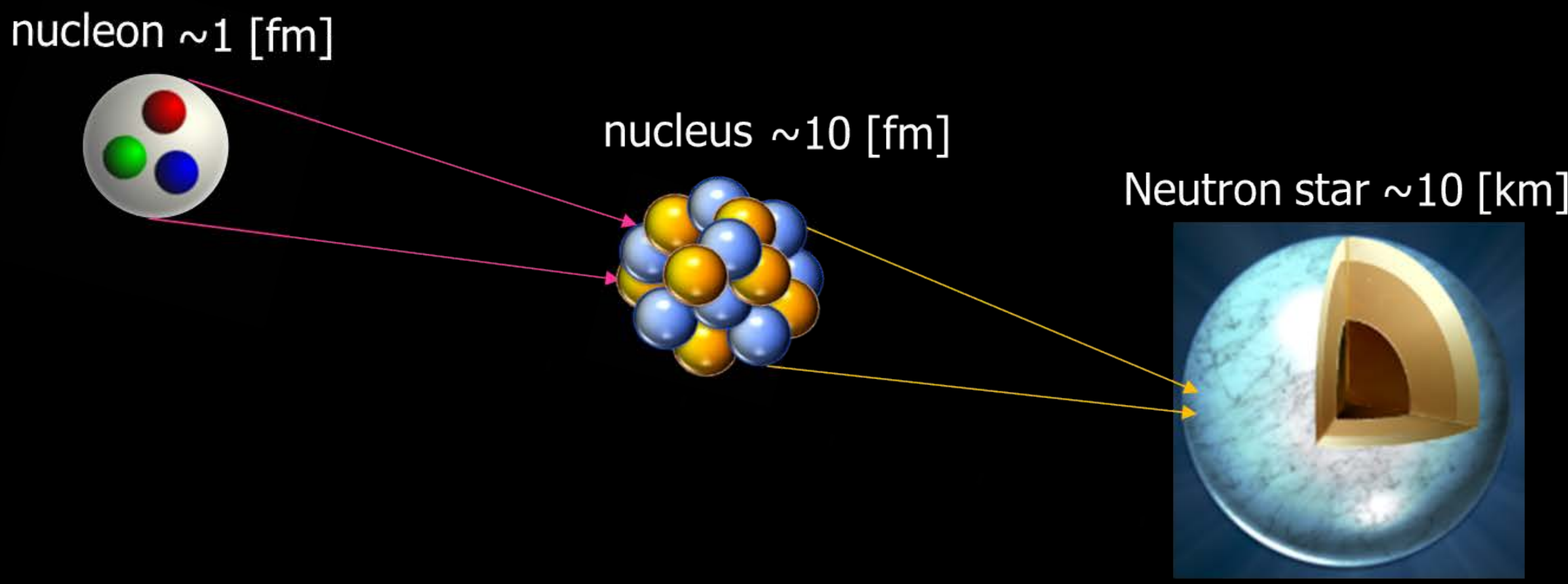




Pauli and van der Waarls at work !



Nuclear Matter, Neutron Matter & Finite Nuclei from LQCD + BHF

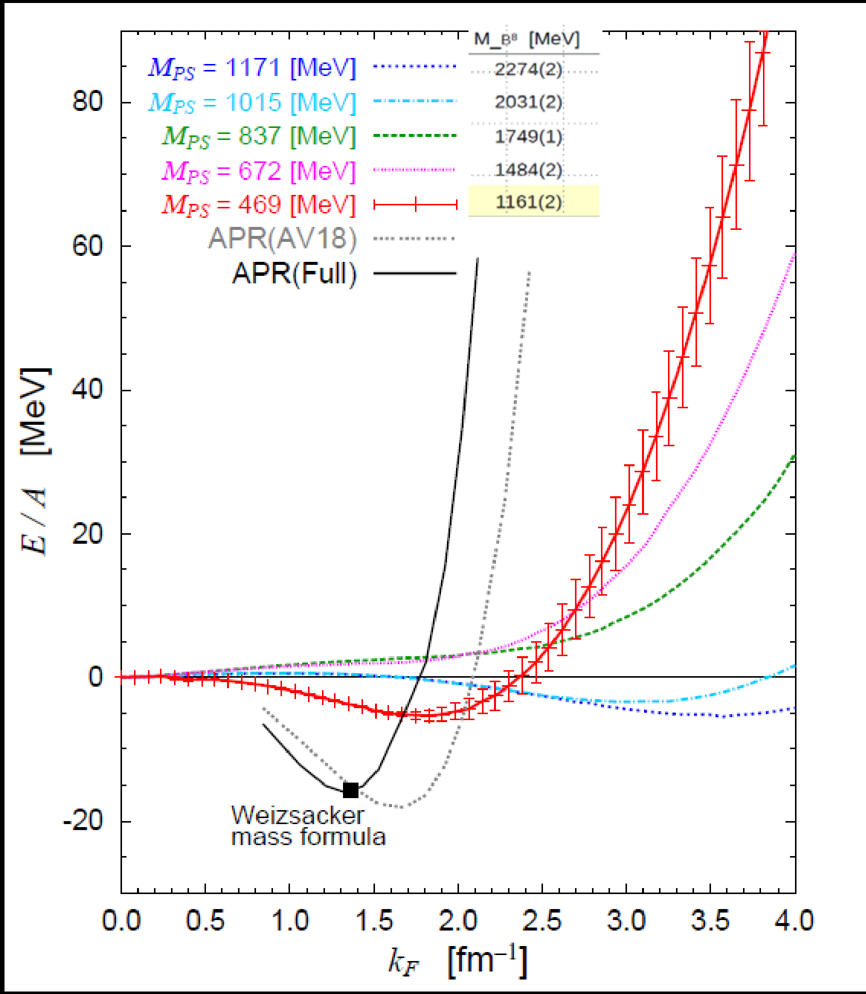


Nuclear EOS from Lattice NN force + BHF calculation

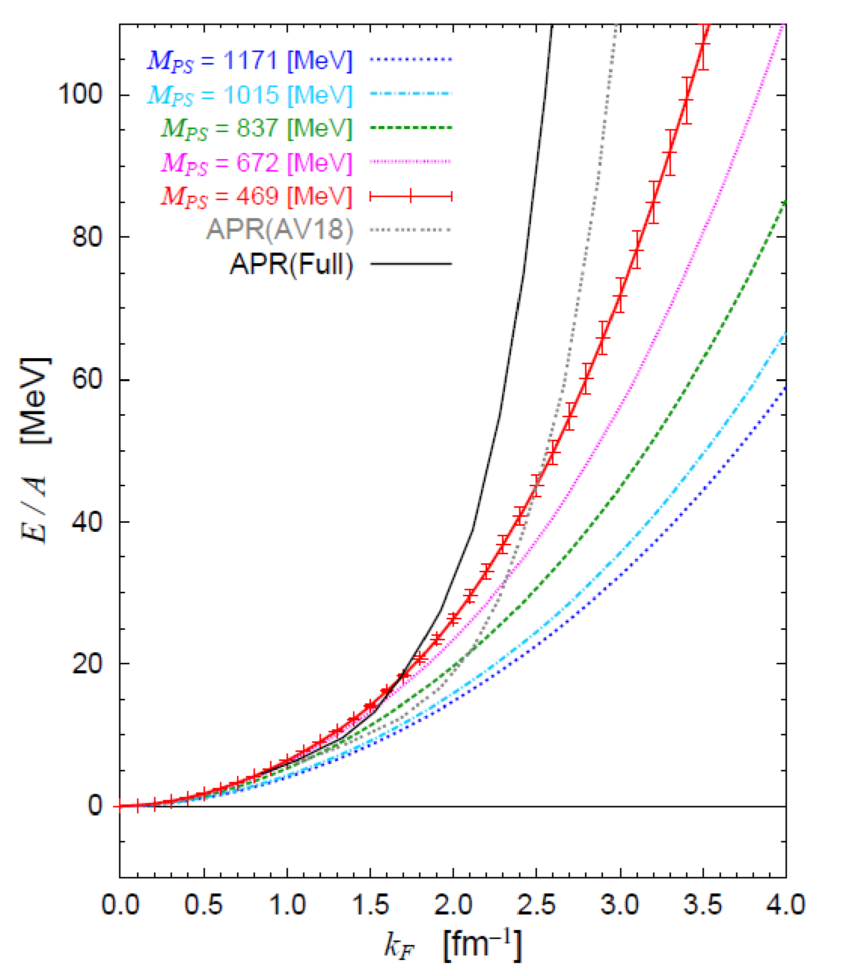
(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

HAL QCD Coll., Phys. Rev. Lett. 111 (2013) 112503

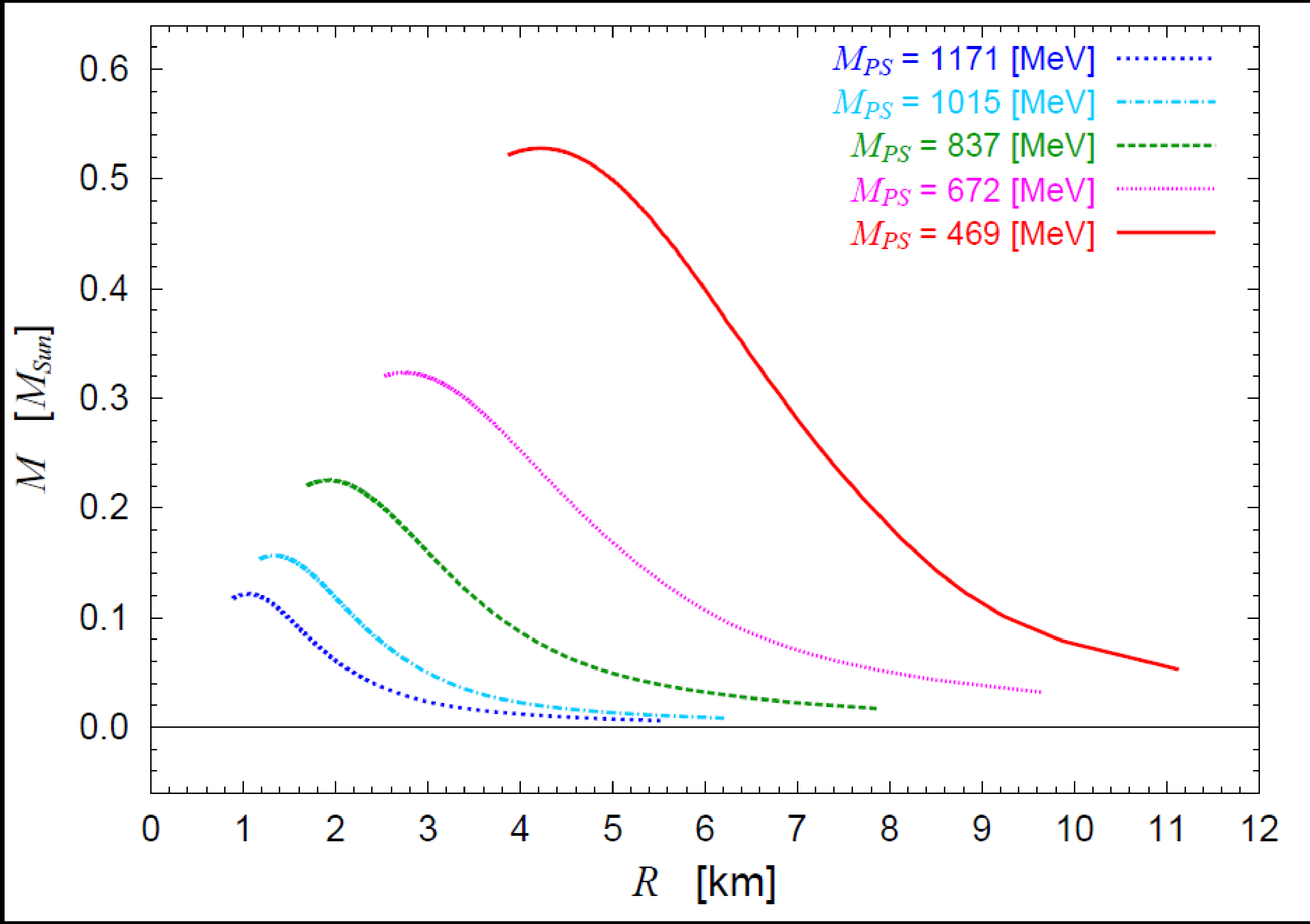
Nuclear Matter



Neutron Matter

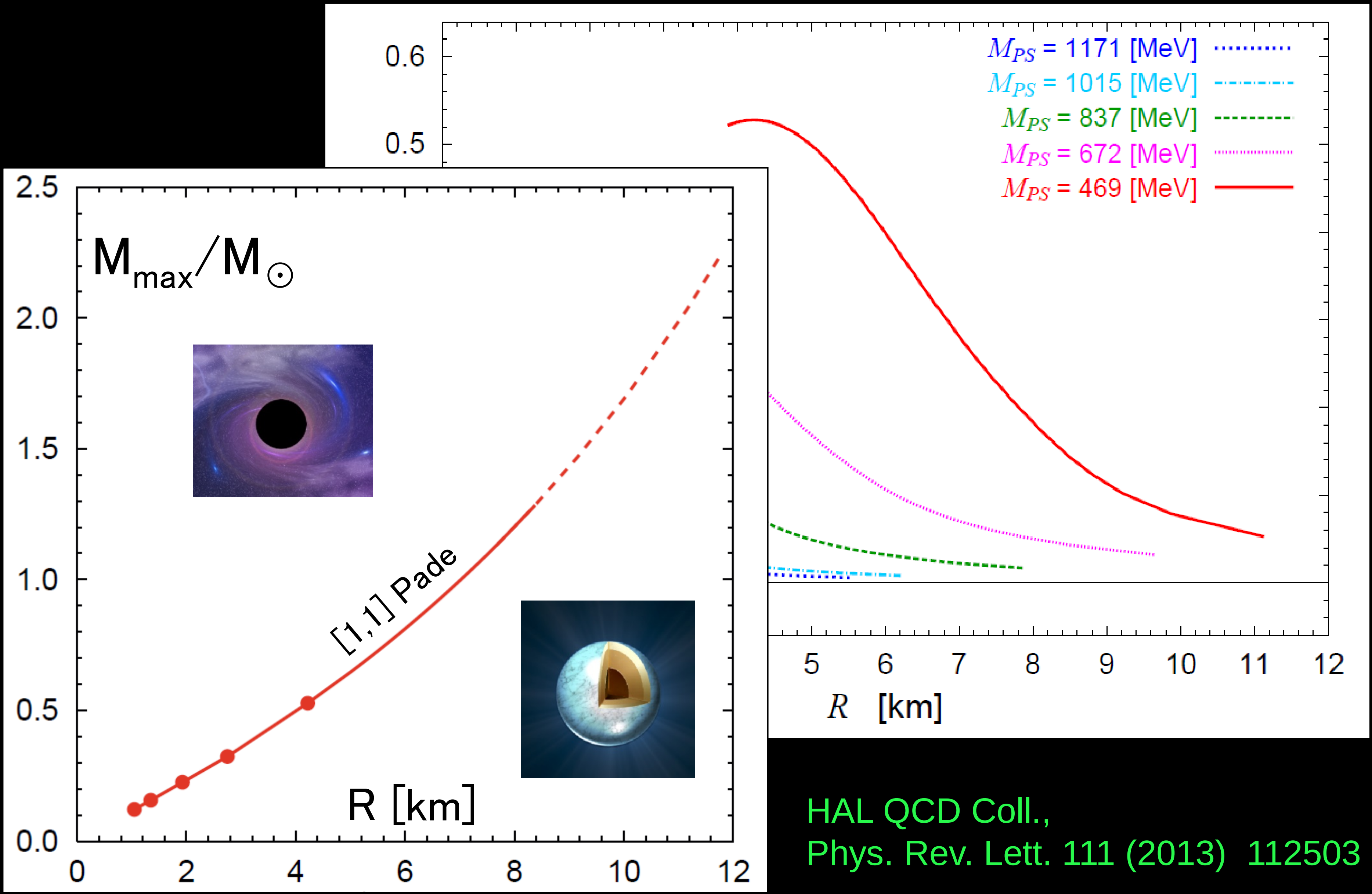


Neutron Star from "Lattice EOS"



HAL QCD Coll.,
Phys. Rev. Lett. 111 (2013) 112503

Neutron Star from “Lattice EOS”



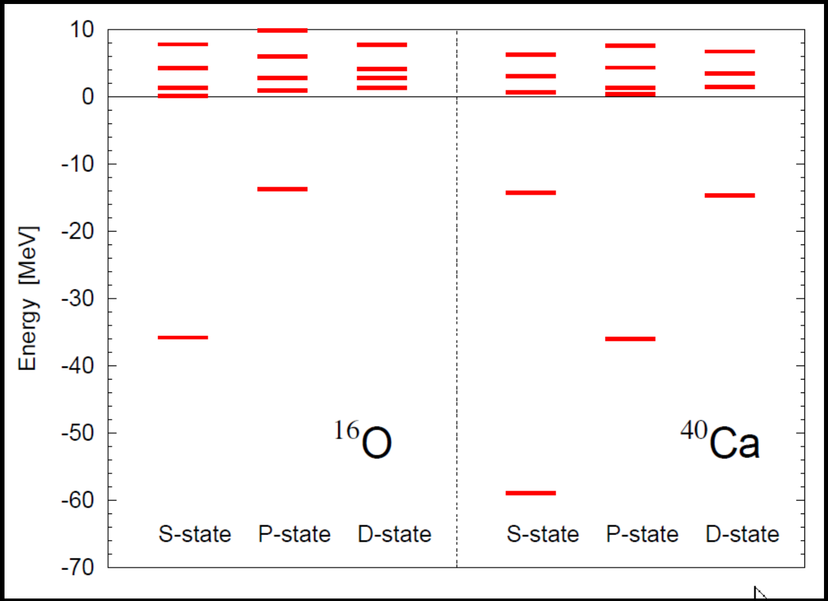
HAL QCD Coll.,
Phys. Rev. Lett. 111 (2013) 112503

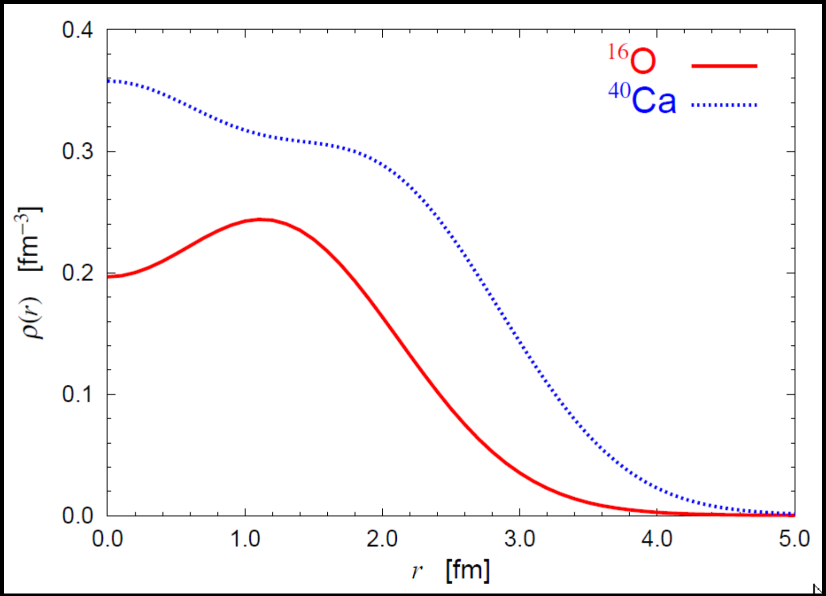
Finite Nuclei from Lattice NN force + BHF calculation

(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

Inoue et al. [HAL QCD Coll.], arXive 1408.4892

Bound nuclei start to appear from m_π=470 MeV



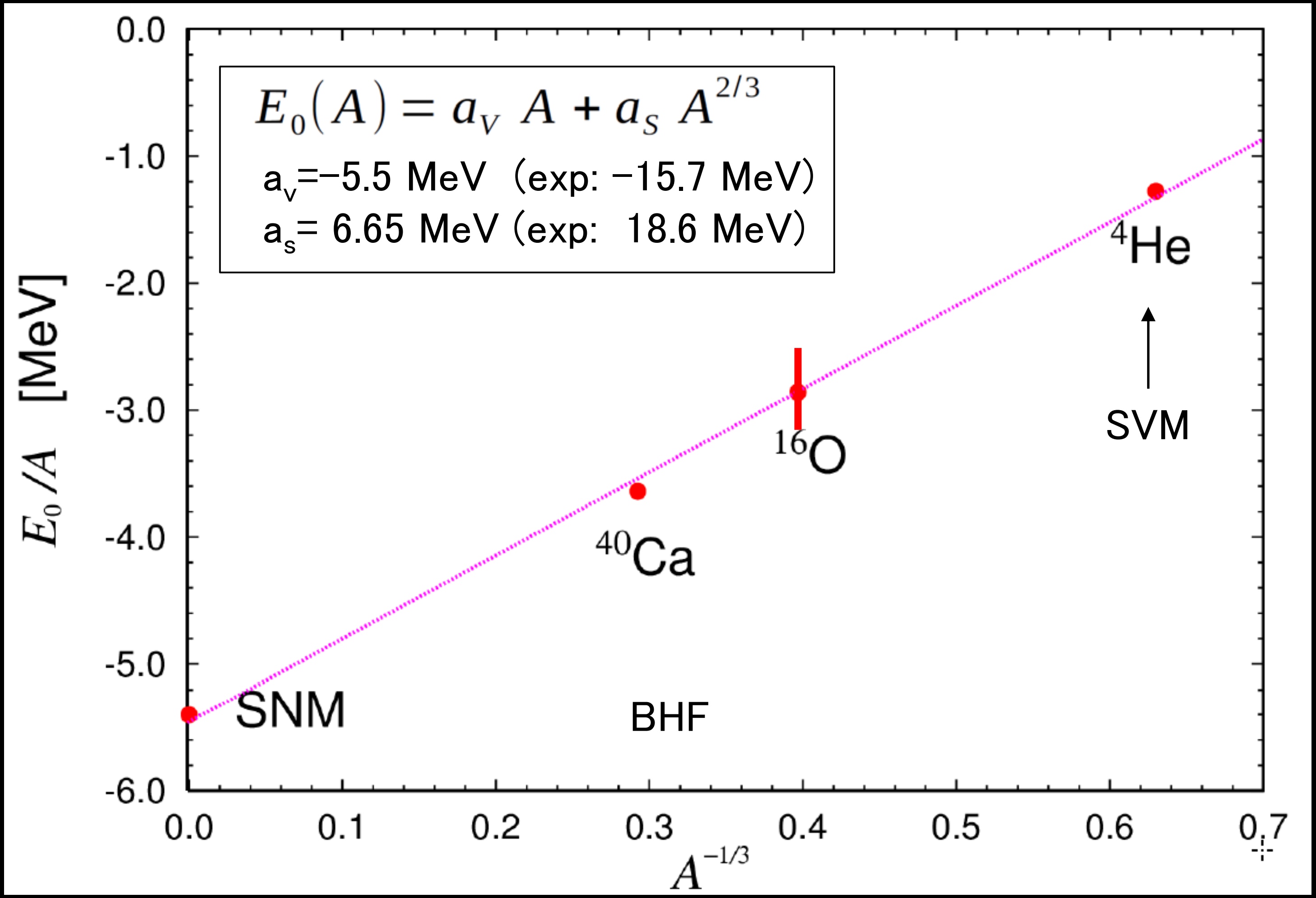


	Single particle level				Total energy		Radius
	$1S$	$1P$	$2S$	$1D$	E_0	E_0/A	$\sqrt{\langle r^2\rangle}$
^{16}O	−35.8	−13.8			−34.7	−2.17	2.35
^{40}Ca	−59.0	−36.0	−14.7	−14.3	−112.7	−2.82	2.78

Nuclear Binding Energy from Lattice NN Force

Inoue et al. [HAL QCD Coll.], arXive 1408.4892

Bethe-Weizacker behavior at m_π=470 MeV



Summary

1. From LQCD to Compact Stars

- The best but hardest strategy : solve the sign problem
- Second and doable strategy (HAL QCD) : derive the BB and BBB forces
  → EoS (with hyperons and 3-body forces) based on LQCD

2. BB forces from LQCD

- T=V+GVT (HAL QCD method) is lattice friendly:
  V is L-insensitive, all the data for t > 1 fm are signals, etc.
- LQCD at unphysical points : m_π=470-1170MeV, L～4fm
  → quark-mass dependence of the BB forces
  origin of the short-range repulsion (Pauli at work)
- Physical-point simulations are on-going by K-computer.

3. Nuclear/Nuutron matter and Finite Nuclei from LQCD

- Neutron star becomes heavier as quark mass decreases
- Finite nuclei start to be bound at (and possible below) m_π=470MeV.

Present un-physical point simulation
for single and multi-baryons

On-going physical point simulation
for single and multi-baryons in K

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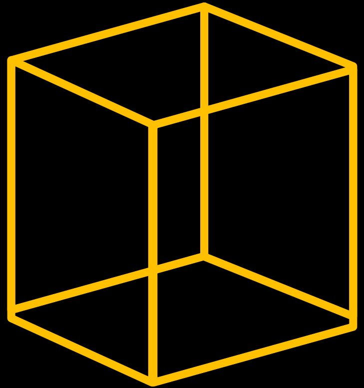

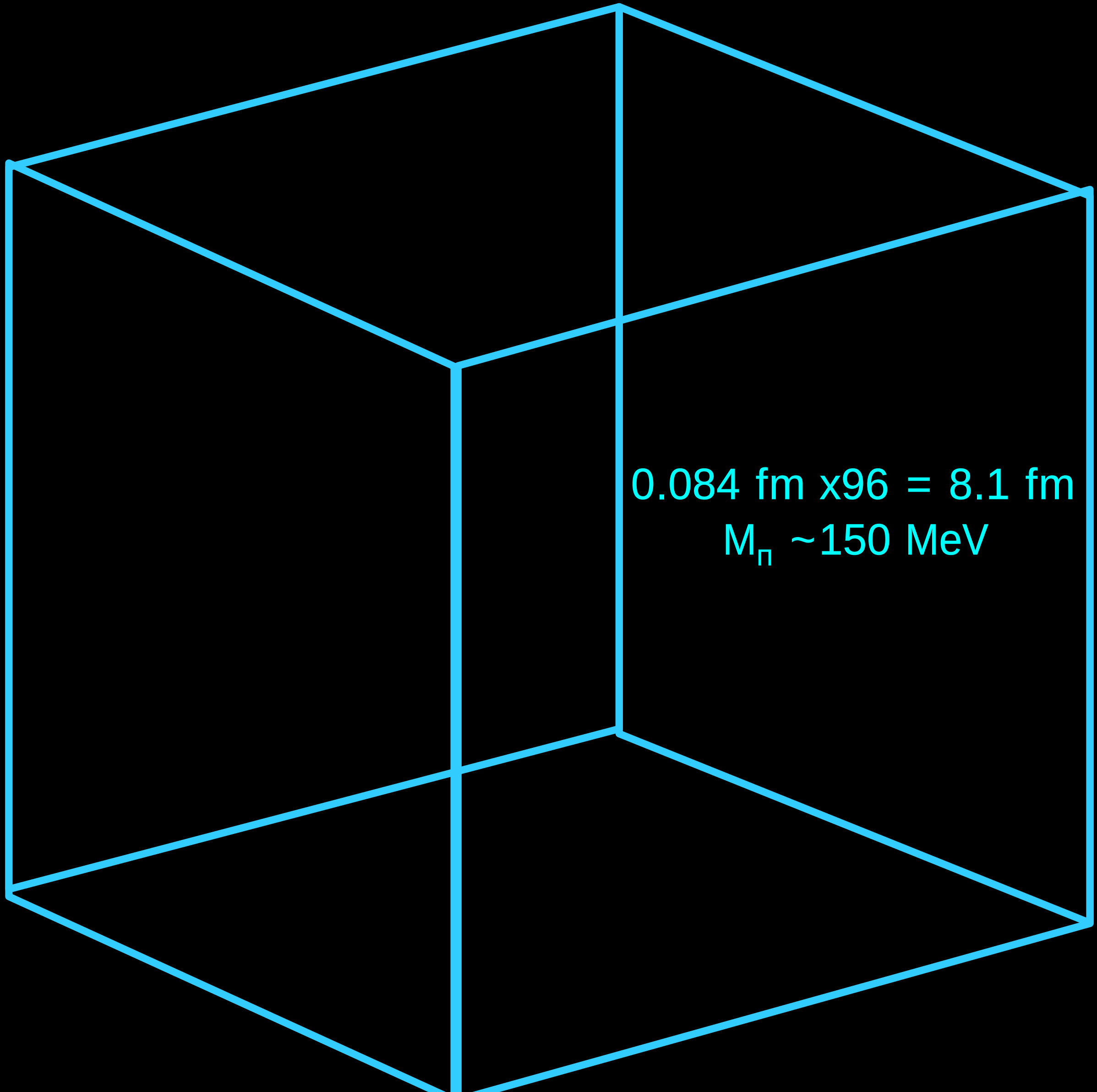

END