High Density Matter from QCD

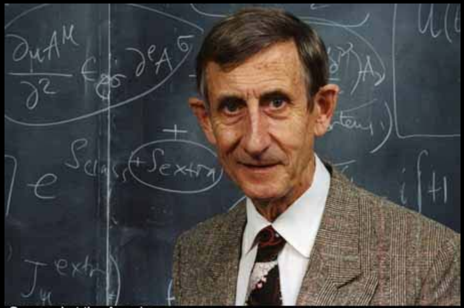
https://www.youtube.com/watch?v=MTvgnYGu9bg

第27回 理論懇シンポジウム「理論天文学・宇宙物理学と境界領域」
2014年 12月24日(水)

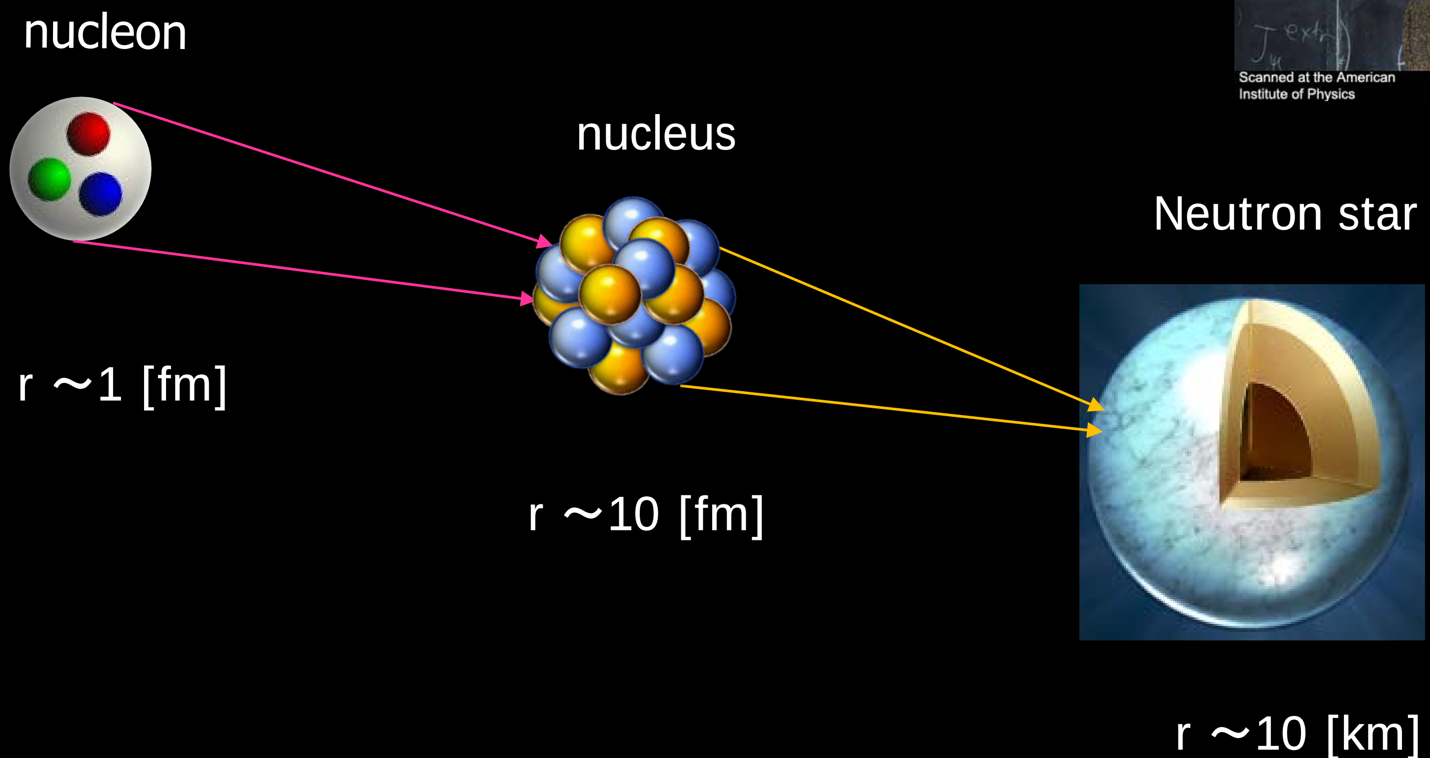
Tetsuo Hatsuda （RIKEN）

The progress of science requires the growth of understanding in both directions, downward from the whole to the parts and upward from the parts to the whole.

From “The Scientist as Rebel” by Freeman J. Dyson



Scanned at the American Institute of Physics



Plan of this Talk

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

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

3. Nuclear & Neutron Matter from LQCD

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

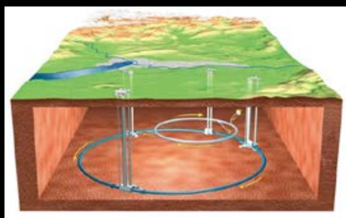
4. Finite Nuclei from LQCD

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

5. Summary

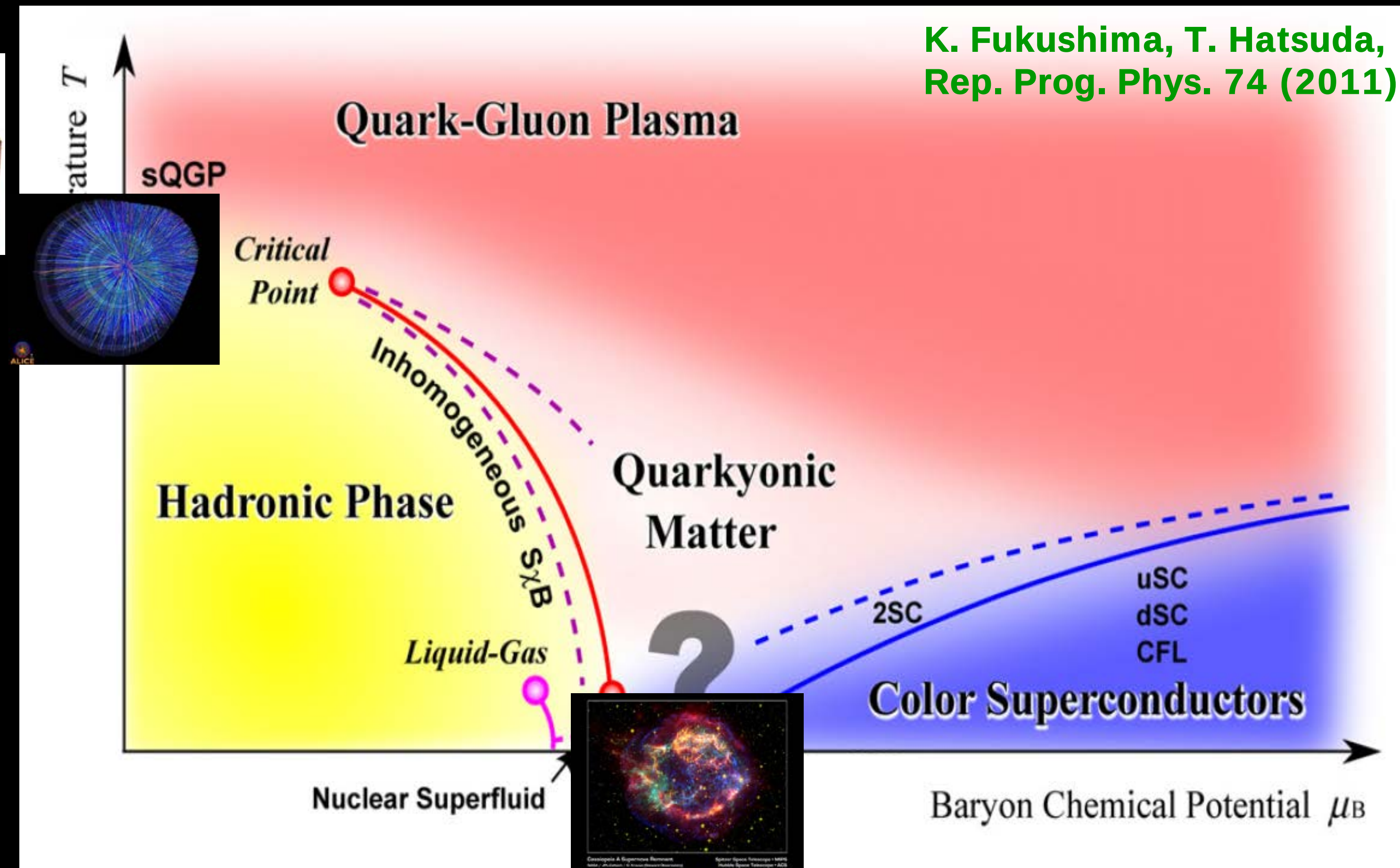
QCD Phase Structure

Physics of
Early Universe



LHC @ CERN

RHIC @ BNL

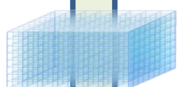


Physics of
Neutron stars
and Black holes

From QCD to Hot Matter

Quantum Chromo Dynamics

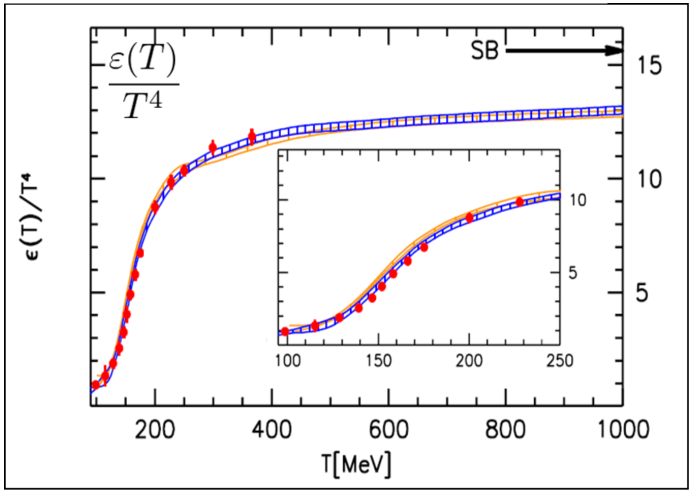
Lattice QCD



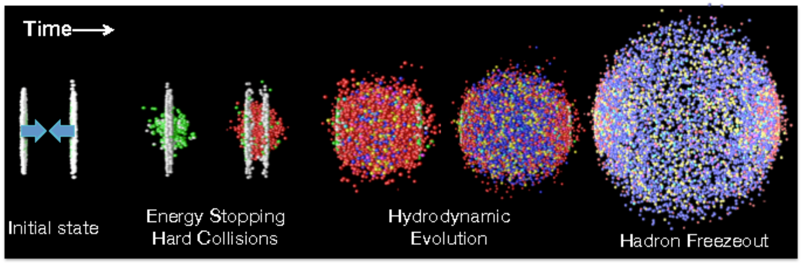
Equation of State for Hot Matter

Relativistic hydrodynamics

Relativistic heavy-Ion collisions

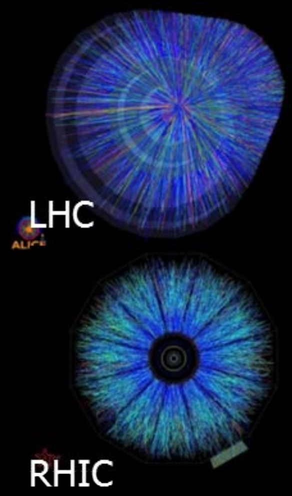


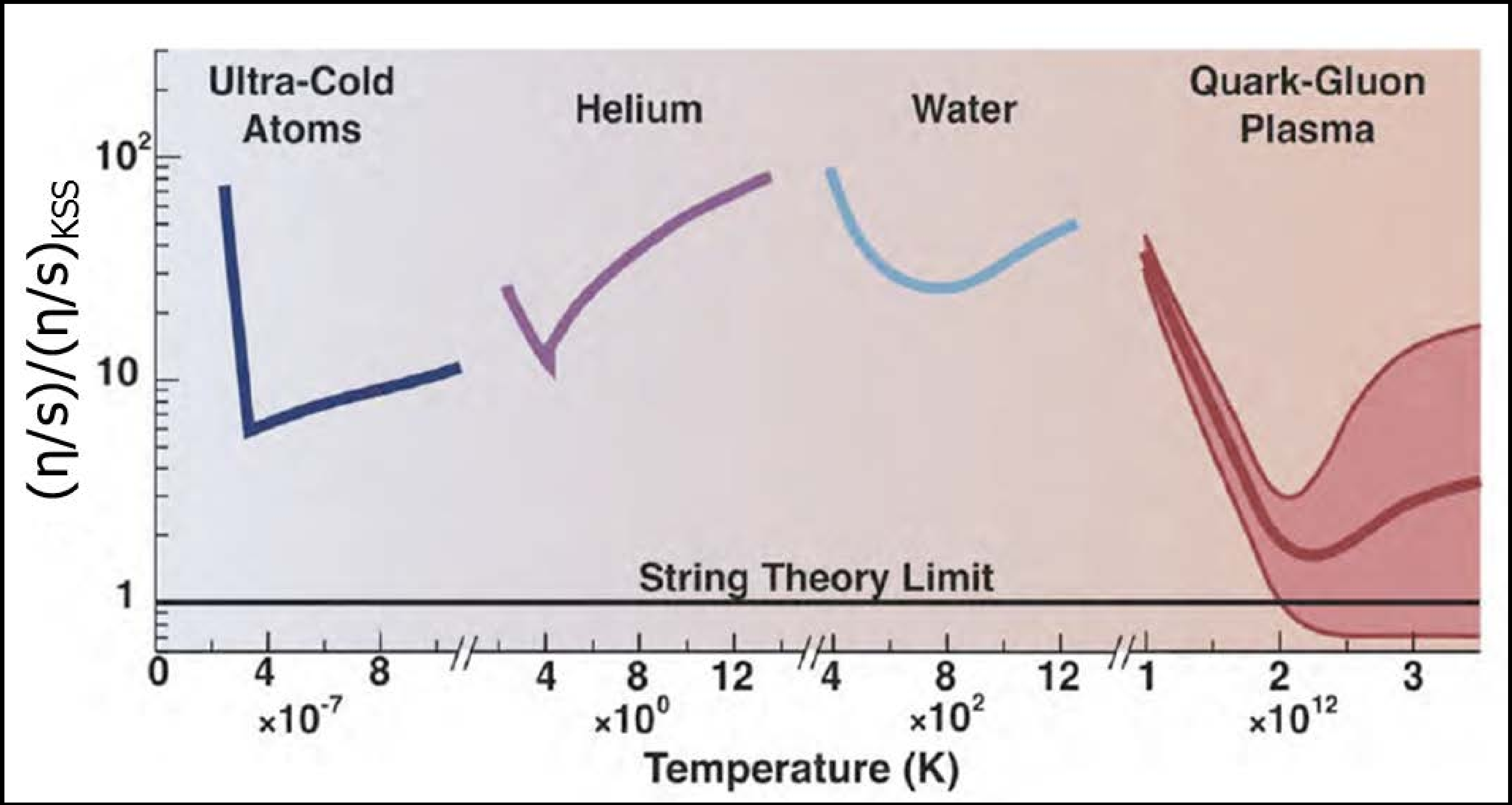
Wuppertal-Budapest Coll. JHEP 1011 (2010) 77



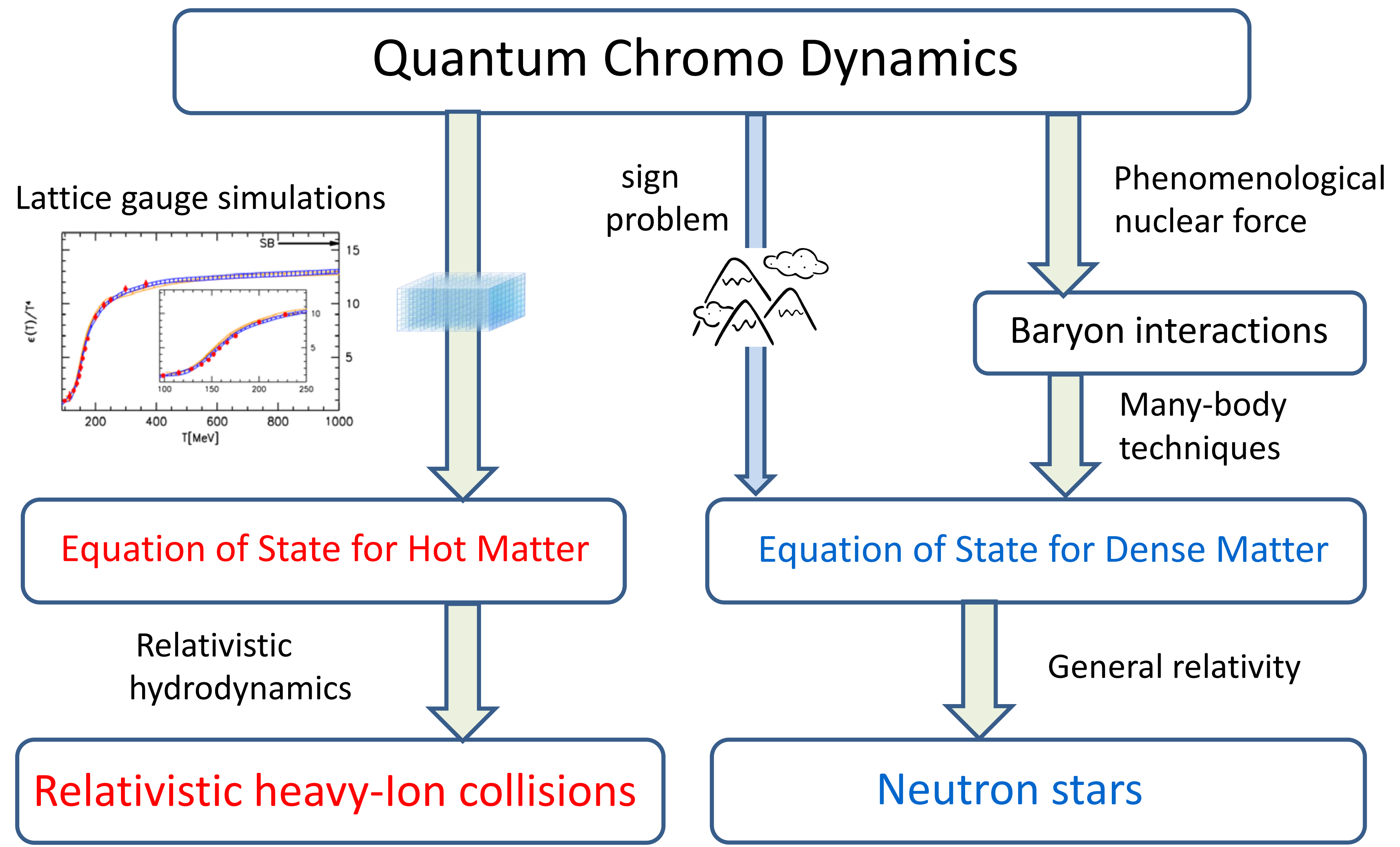
Quark-Gluon Plasma at RHIC/LHC

- high temp.: $T \sim 4 \times 10^{12}$ K
- low viscosity: $\eta/s \sim 1/4\pi$



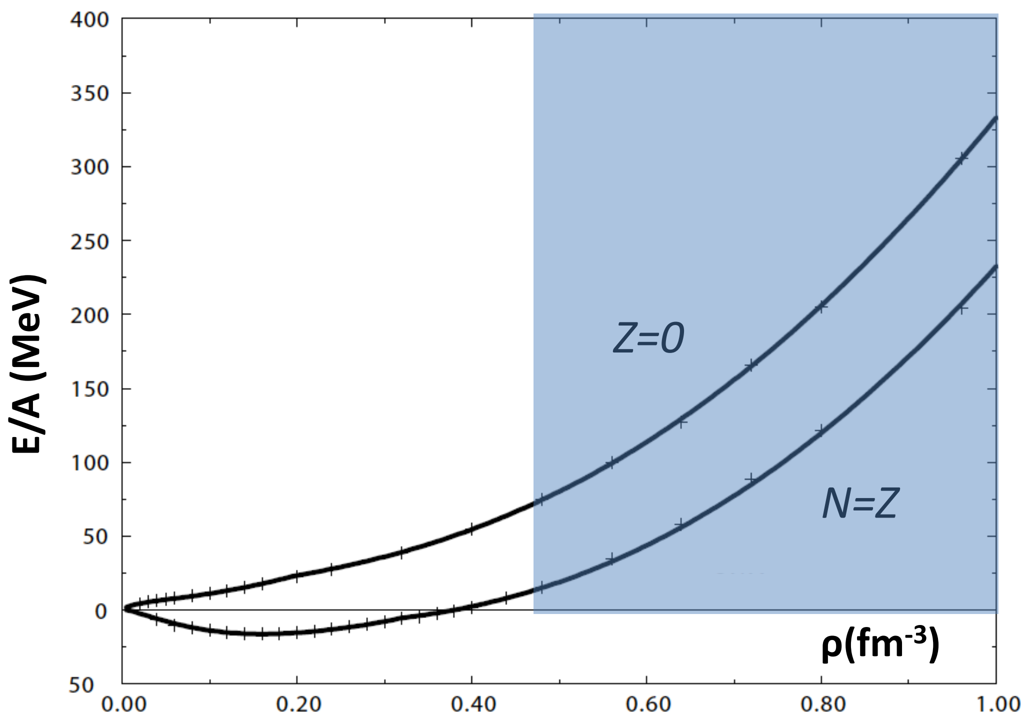


From QCD to Dense Matter



Nuclear Force and dense EOS（nucleons only）

Akmal, Pandharipande & Ravenhall, PRC58 ('98)

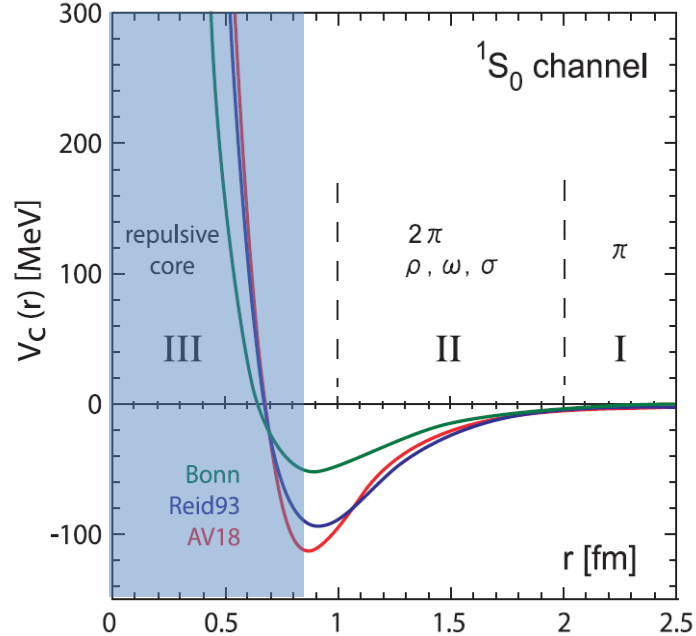


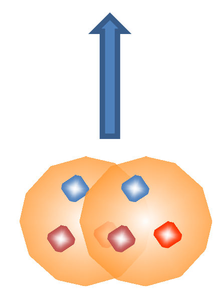
ρ_0
$= 0.16\ \mathrm{fm}^{-3}$

$3\rho_0$

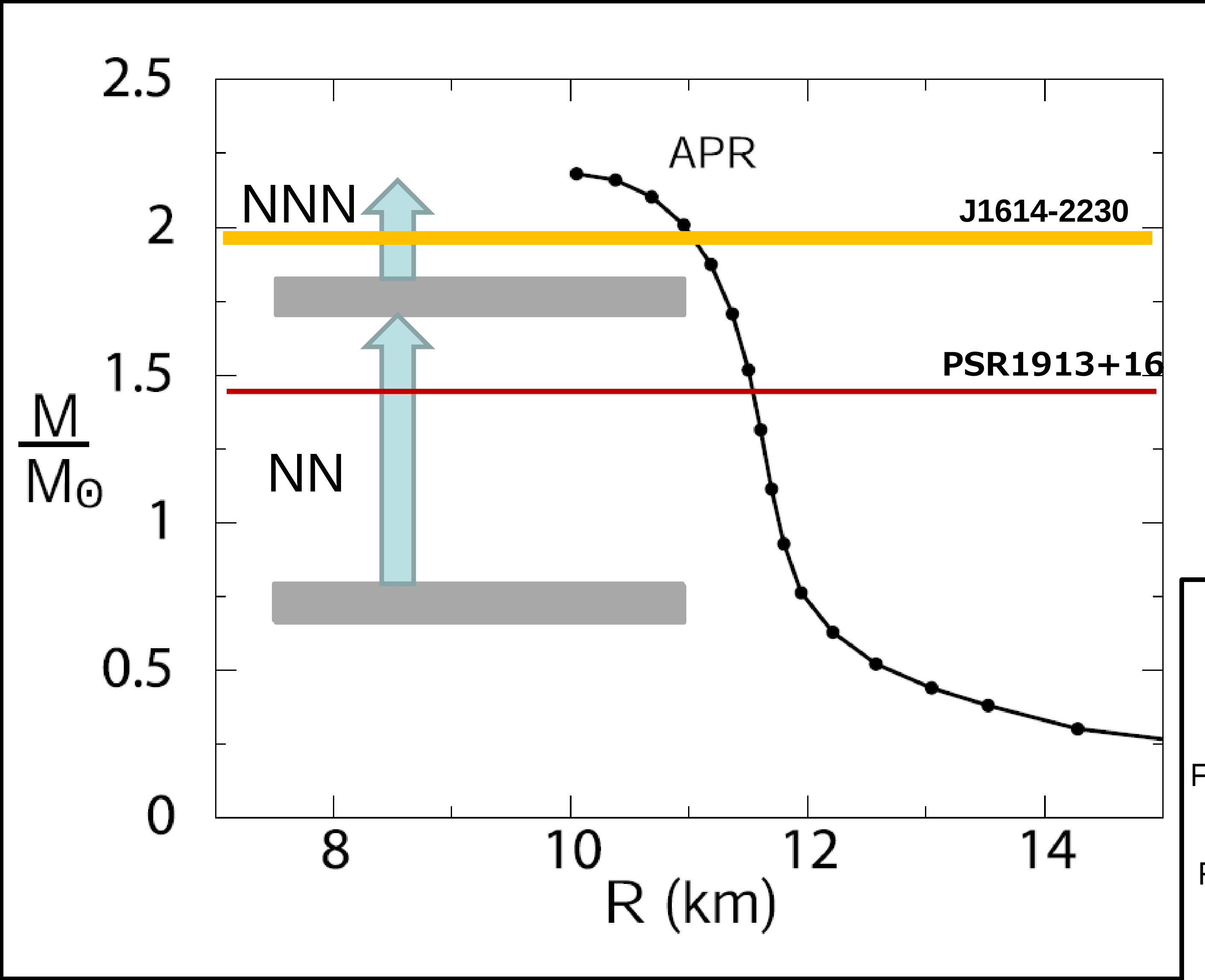
$5\rho_0$

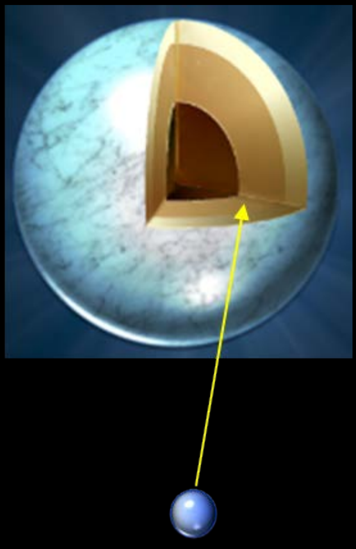
Phenomenological nuclear force

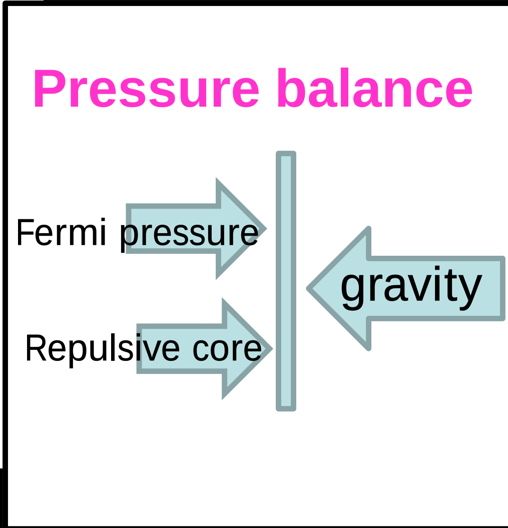




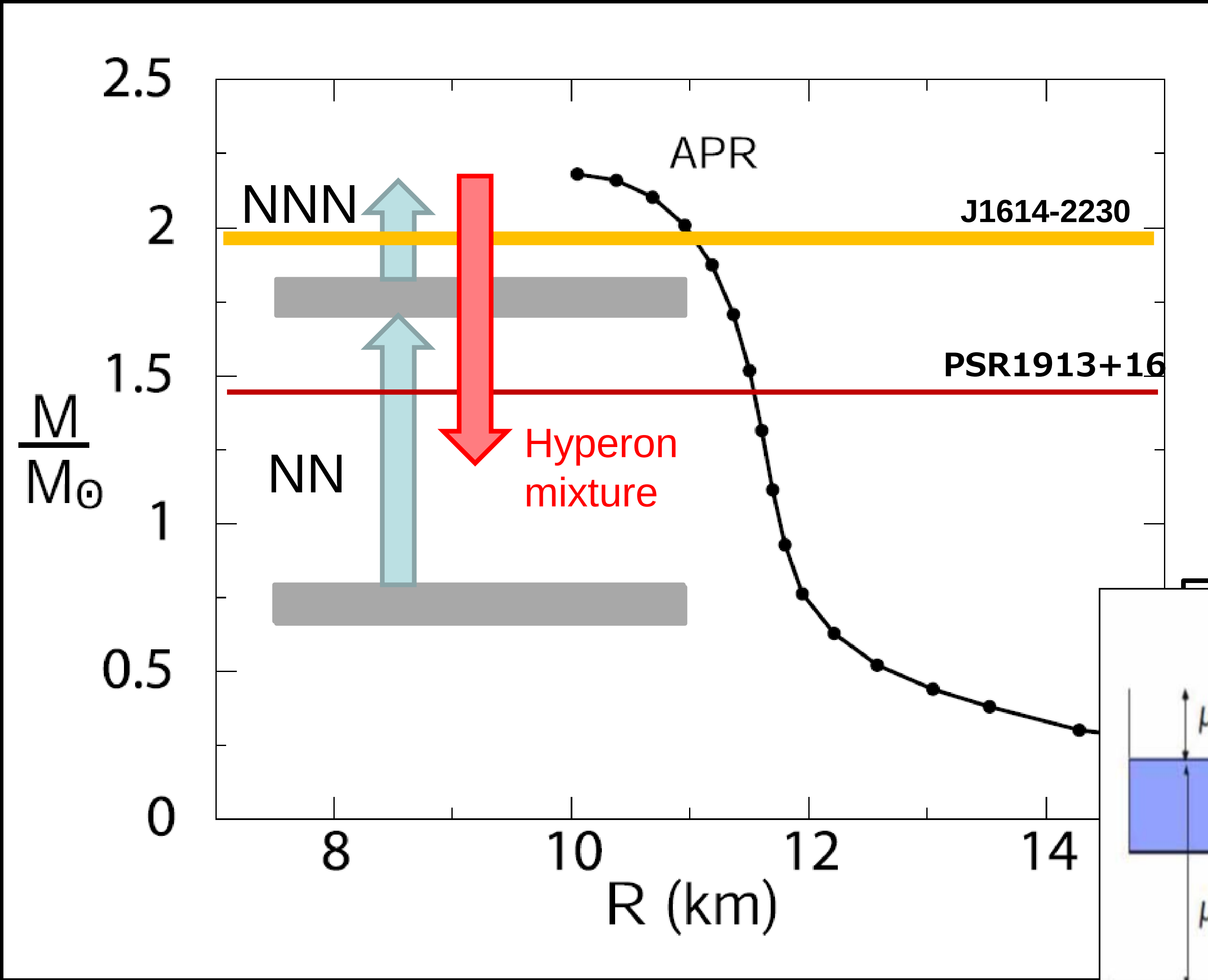
Mass-Radius relation of N$_☆$ (nucleons only)

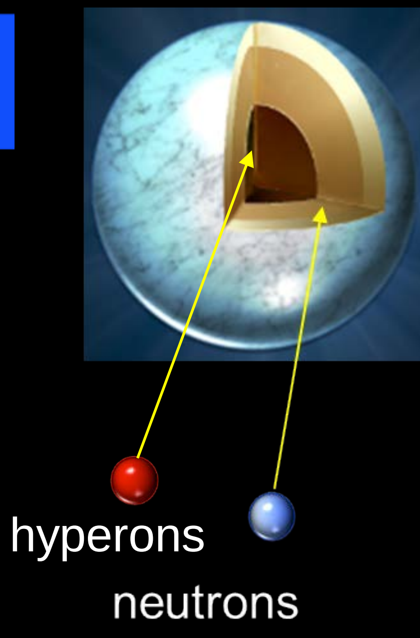


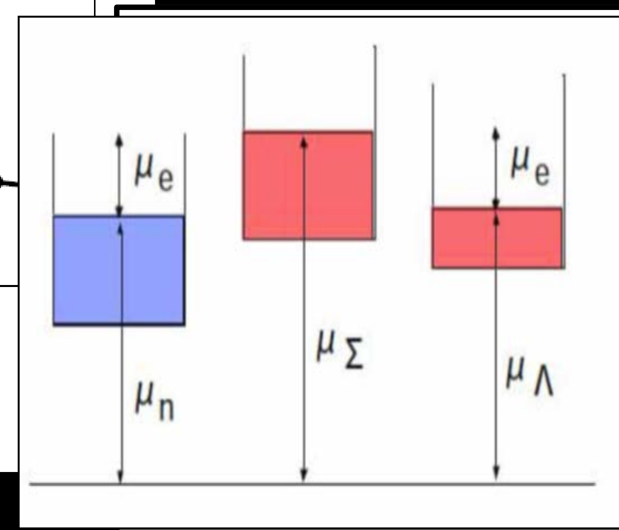




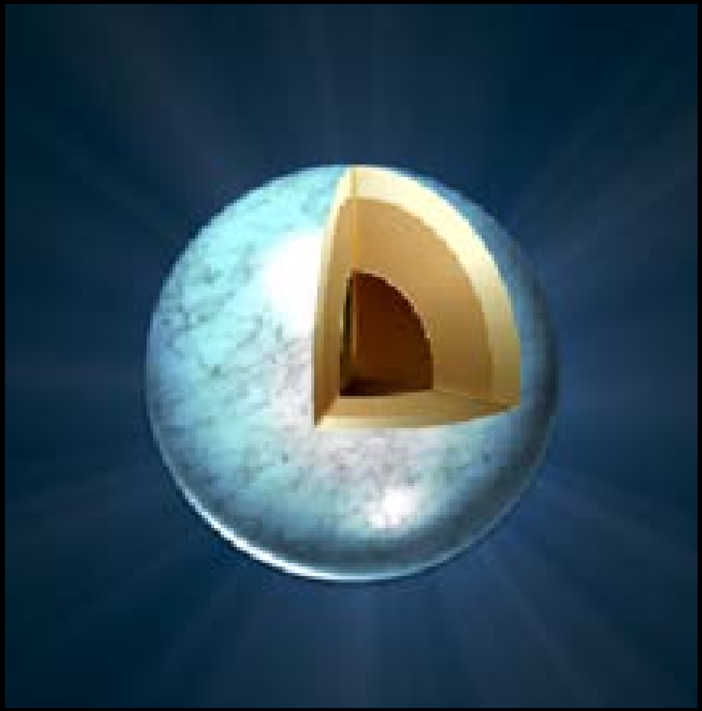
Hyperon Crisis (Takatsuka et al., 2002)

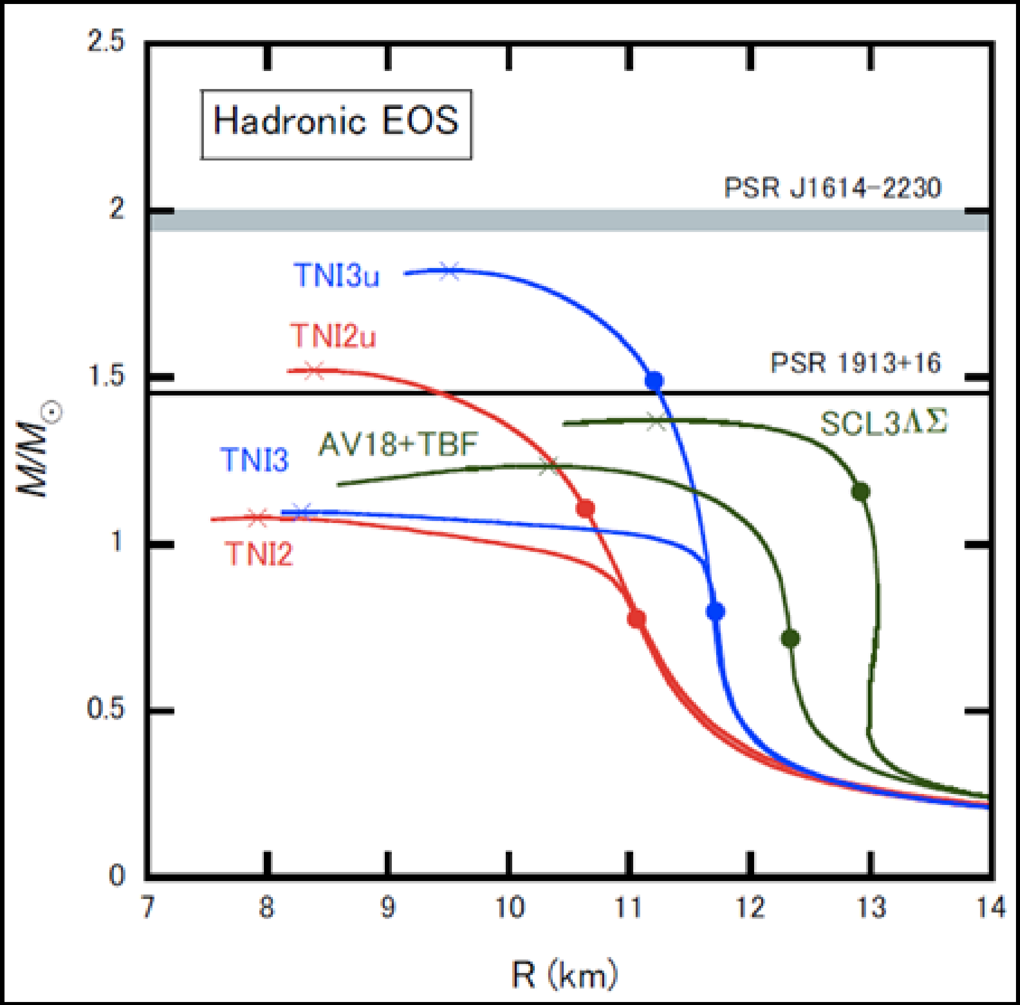






Hyperon Crisis



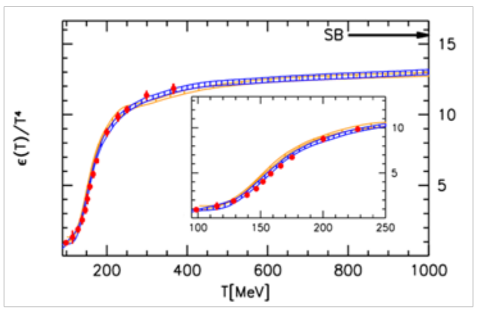


Masuda, Hatsuda & Takatsuka,
Astrophysical Journal Letters 764 (2013) 12

From QCD to Hot/Dense Matter

Quantum Chromo Dynamics

Lattice gauge simulations



sign problem

Lattice QCD simulations

Baryon interactions

Many-body techniques

Equation of State for Hot Matter

Equation of State for Dense Matter

Relativistic hydrodynamics

General relativity

Relativistic heavy-Ion collisions

Neutron stars

Precision QCD

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

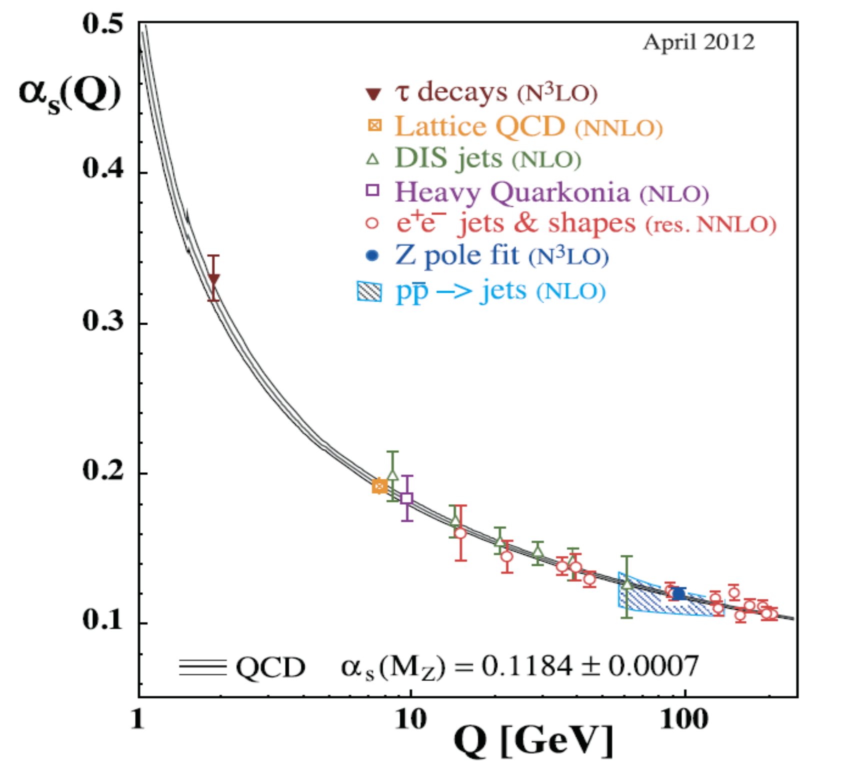
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

Running masses: $m_q(Q)$

quark masses (from lattice QCD)	[MeV] (MS-bar @ 2GeV)
m_u	2.16 (9)(7)
m_d	4.68 (14)(7)
m_s	93.8 (2.4)

FLAG Collaboration update(July 26, 2013)
http://itpwiki.unibe.ch/flag/

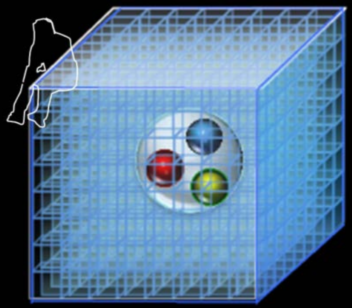
Running coupling: $\alpha_s(Q)=g^2/4\pi$

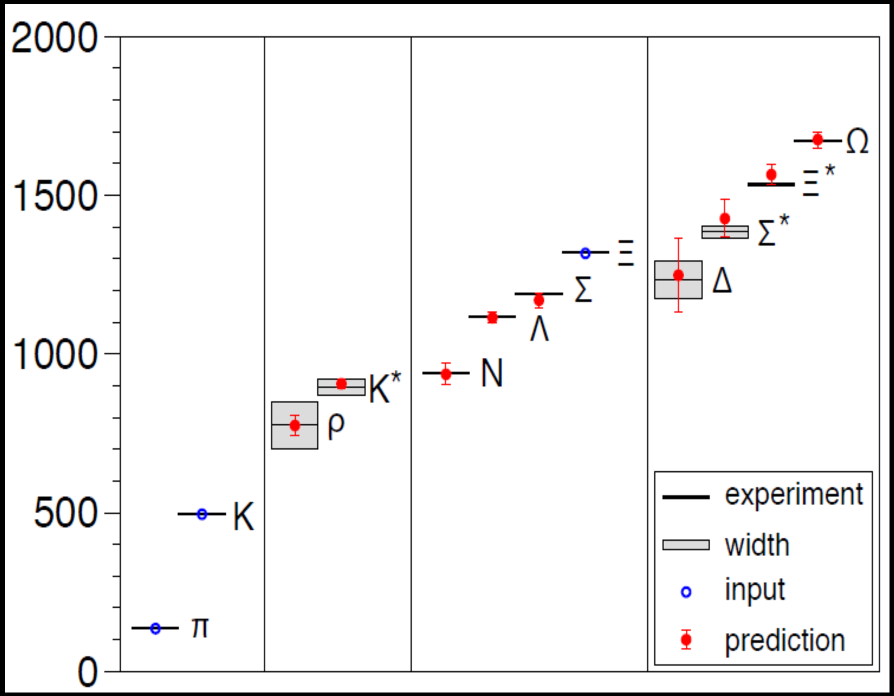


PDG (2012) http://pdg.lbl.gov/

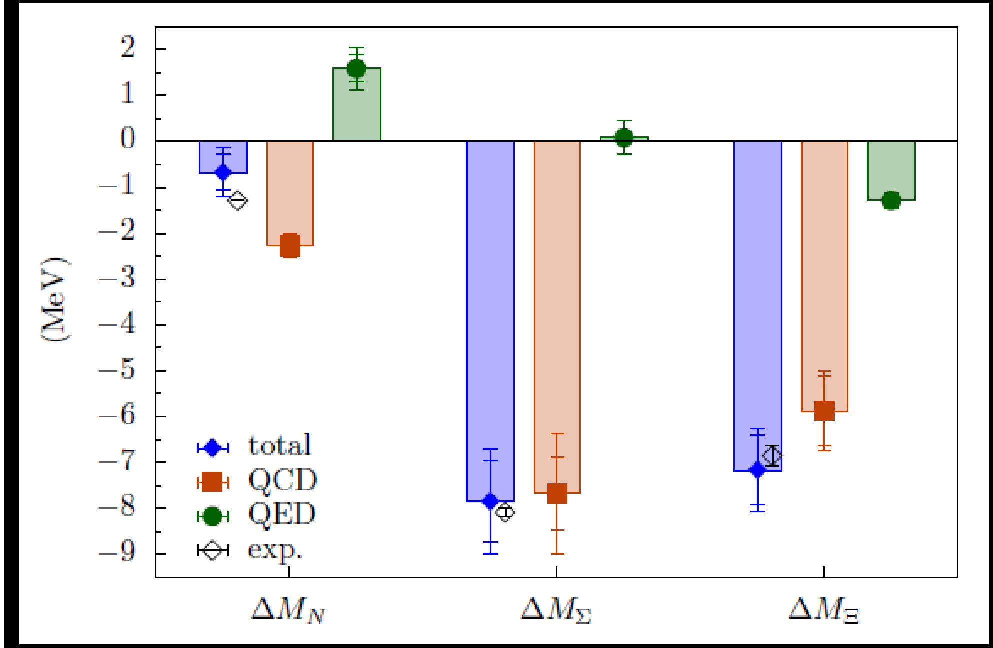
Hadron masses (2008)
m_π > 190 MeV

Hadron masses (2013)
m_π =135 MeV with QED





BMW Collaboration, Science 322 (2008) 1224



BMW Coll.: Phys.Rev.Lett. 111 (2013) 252001

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)

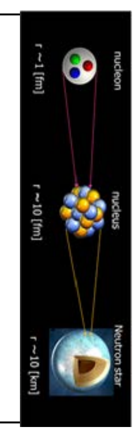
Lattice 2015 (July)
Quark Matter 2015 (Oct.)

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



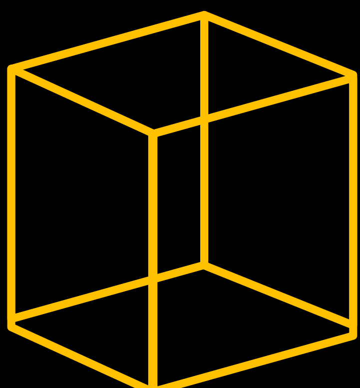
Present un-physical point simulation
for single and multi-baryons

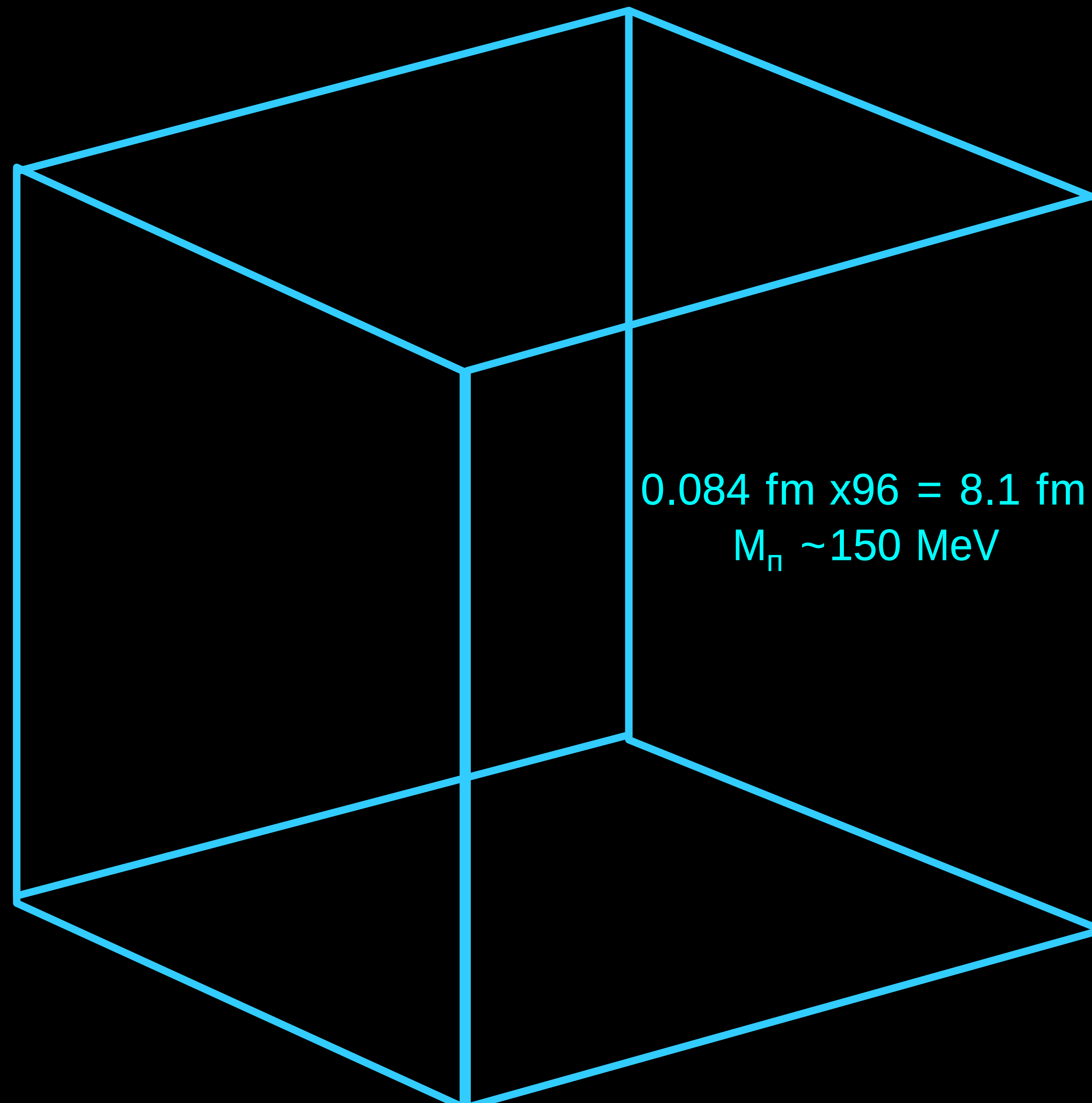
On-going physical point simulation
for single and multi-baryons in K

NEXT YEAR'S TALK
Stay Tuned !!

TODAY'S TALK

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



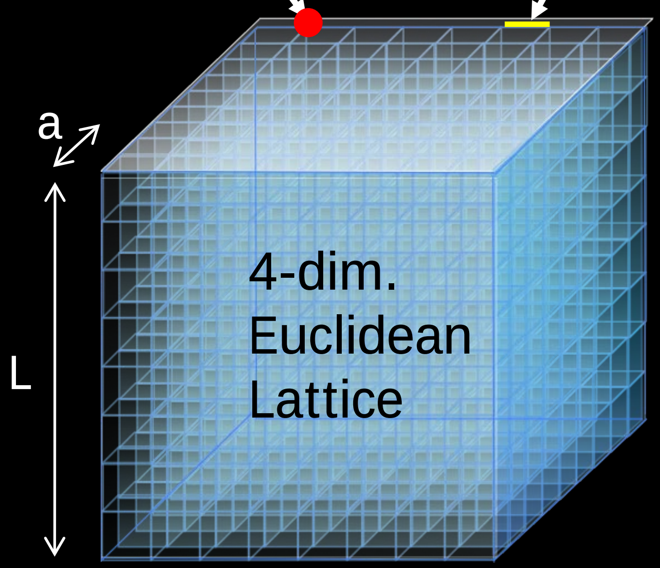


格子QCD

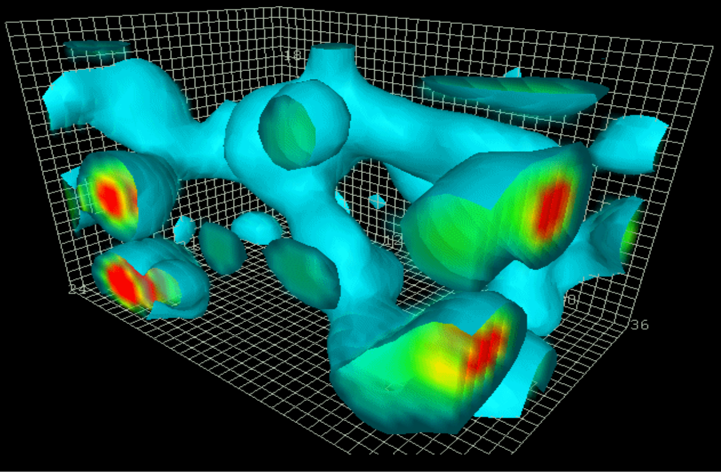
K. Wilson
(1936-2013)

quarks q on the sites

gluons $U_\mu = exp(iagA_\mu)$ on the links



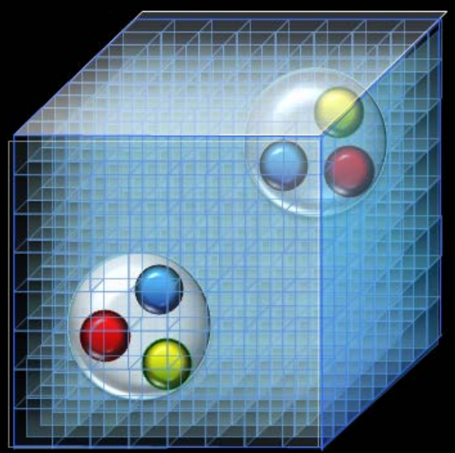
$$Z = \int [dU][dqd\bar{q}] \ \exp\left[-\int d\tau d^3x \mathcal{L}_{\rm E}\right]$$

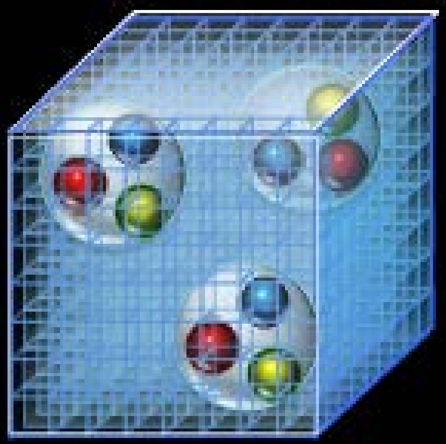


- well defined statistical system (finite a and L)
- gauge invariant
- fully non-perturbative

→ Numerical simulations

Baryon Forces from LQCD



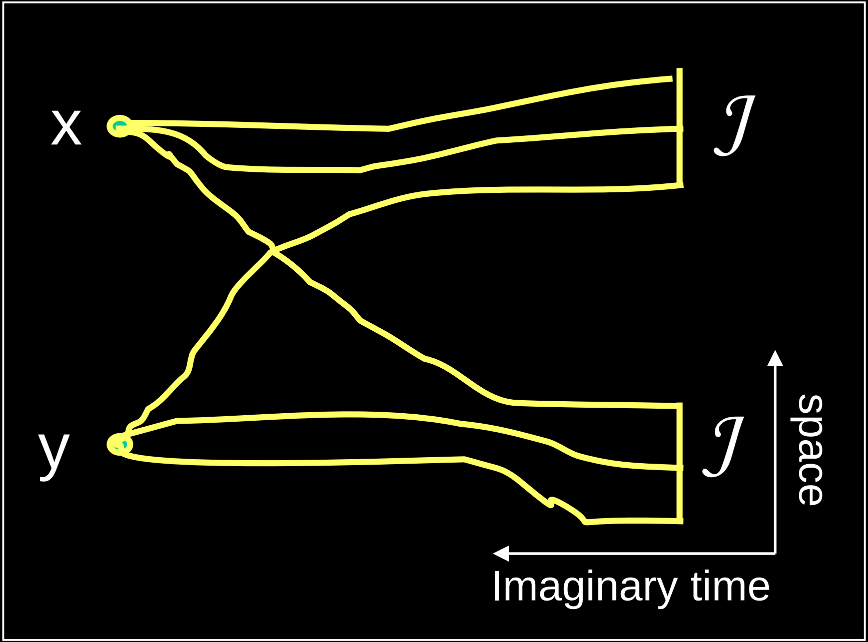


Hadrons to Atomic nuclei
HAL
from Lattice QCD

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, T. Iritani
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 :

$E_0(L)$ → phase shift

Luescher, Nucl. Phys. B354 (1991) 531

HAL QCD Method

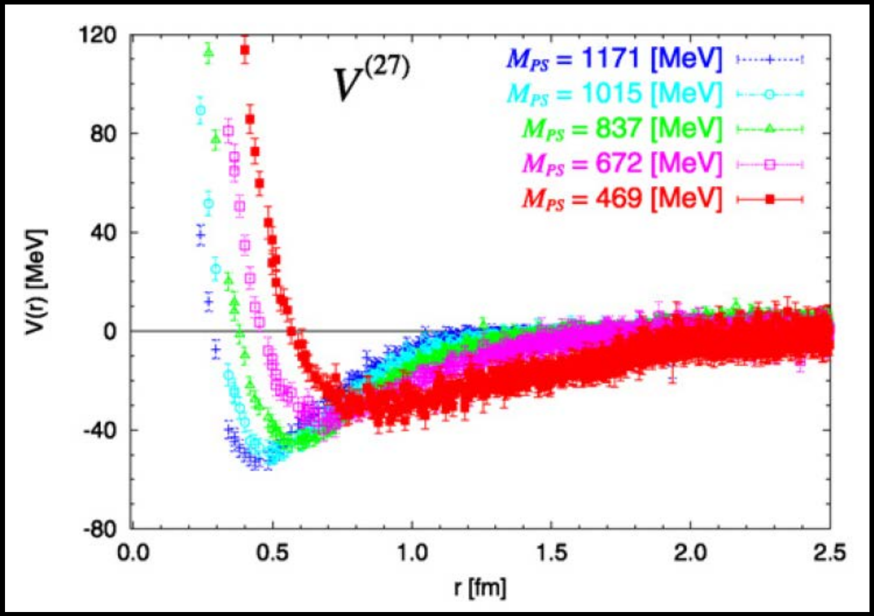
$\phi(r,t)$ → kernel → phase shift

Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001
Comp. Sci. Dis. 1 (2009) 015009
HAL QCD Coll., PLB 712 (2012) 437

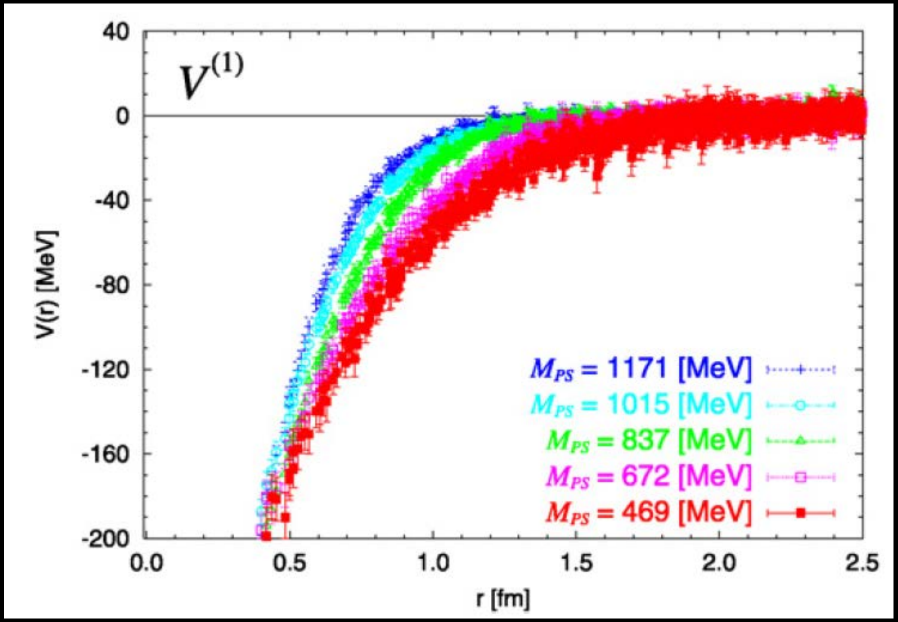
BB Forces in 3-flavor QCD

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

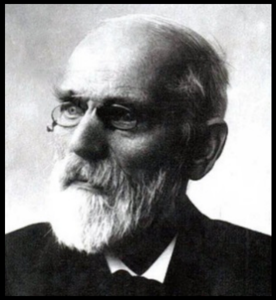
PP (uud-uud) channel
(partial) Pauli blocking



H (uds-uds) channel
No Pauli blocking



Pauli and van der Waarls
at work !

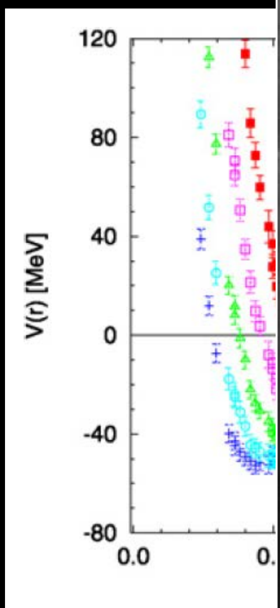


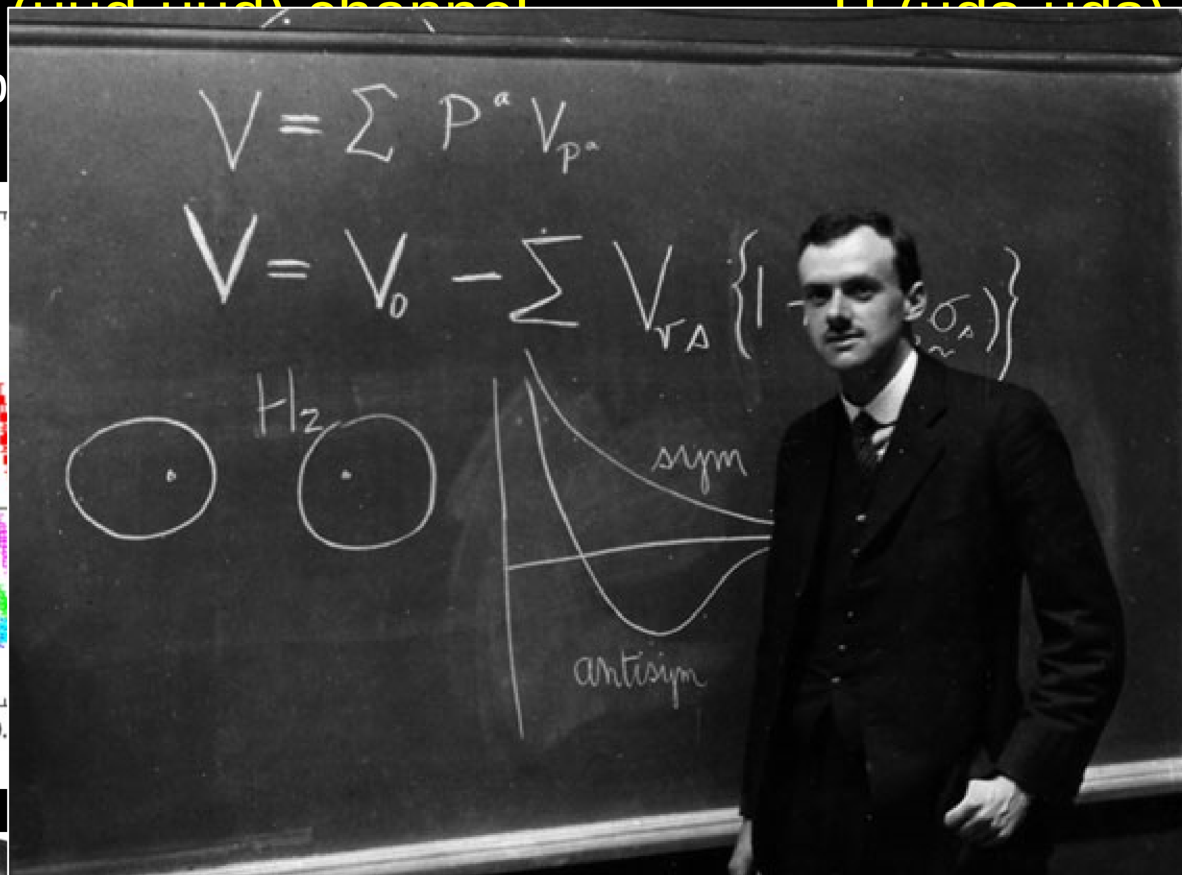
BB Forces in 3-flavor QCD

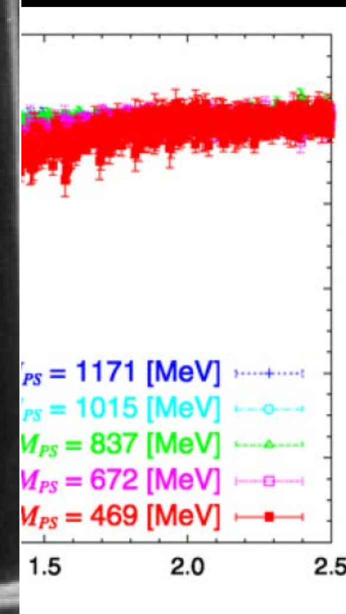
HAL QCD Coll.
Phys. Rev. Lett. 106 (2011) 162002
Nucl. Phys. A881 (2012) 28

PP ... channel

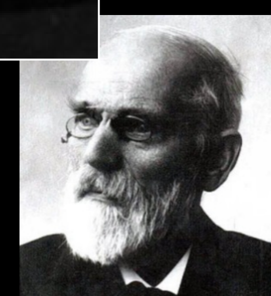
(p ... cking



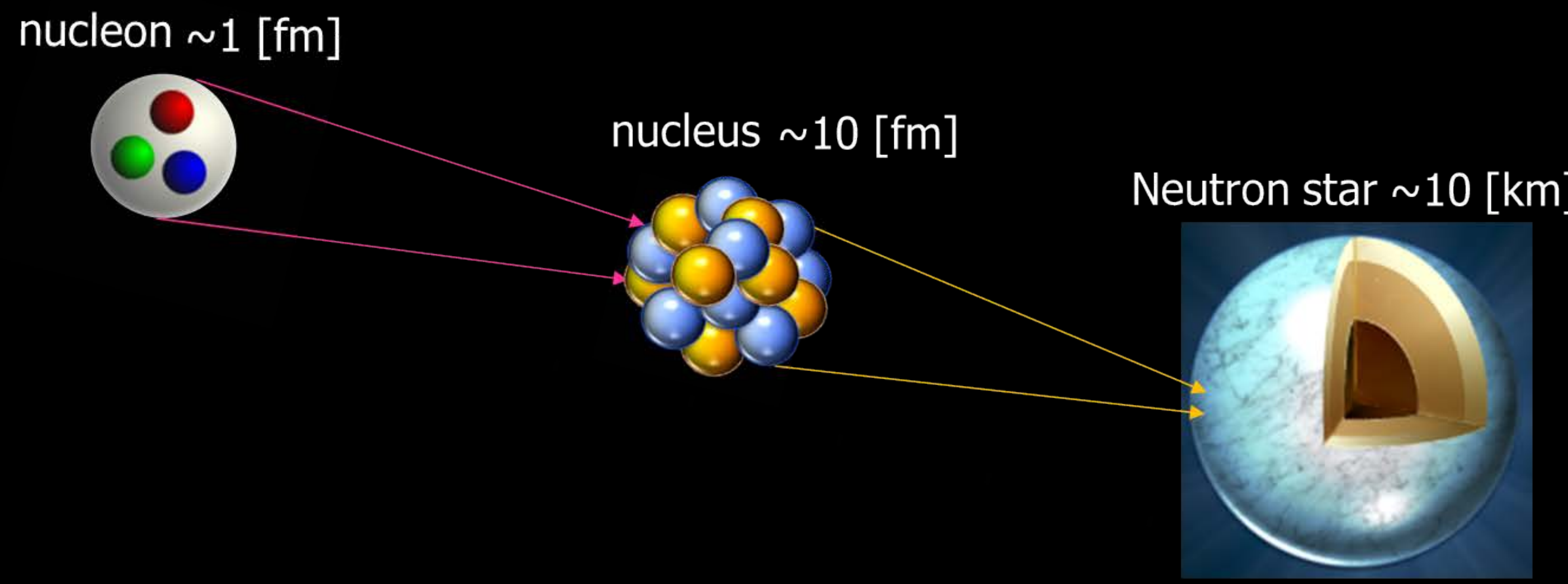




Pauli and van der Waarls
at work !



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

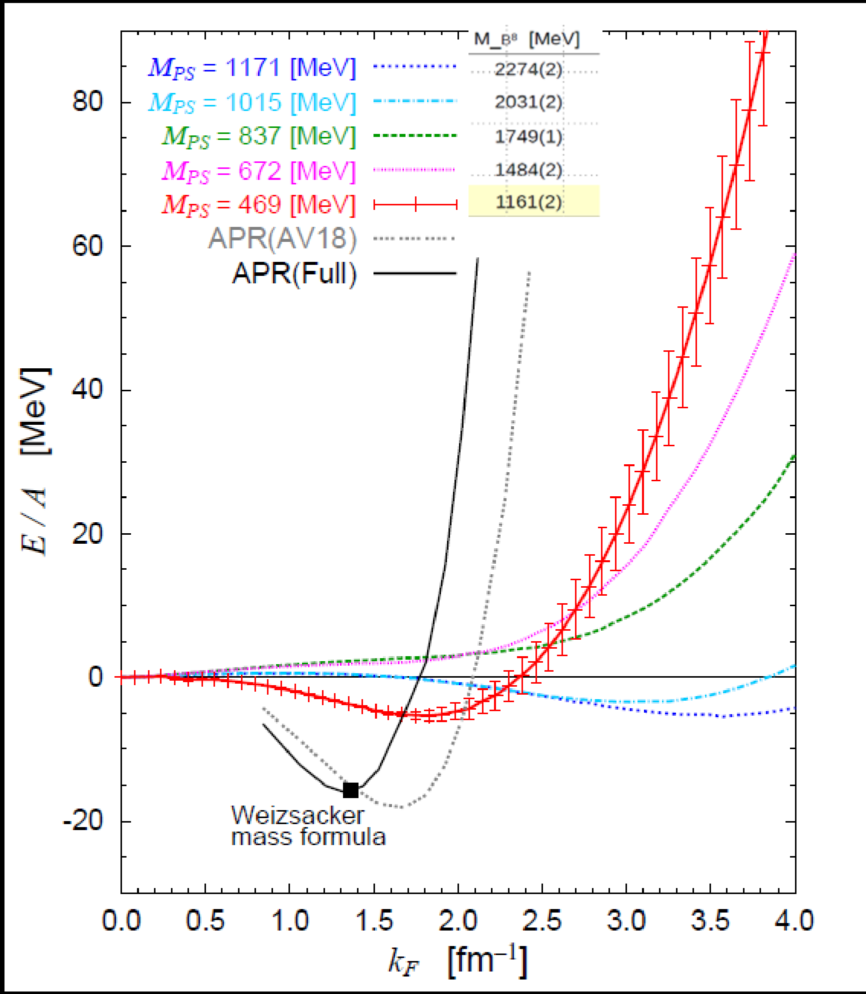


Nuclear EOS from Lattice NN force + BHF calculation

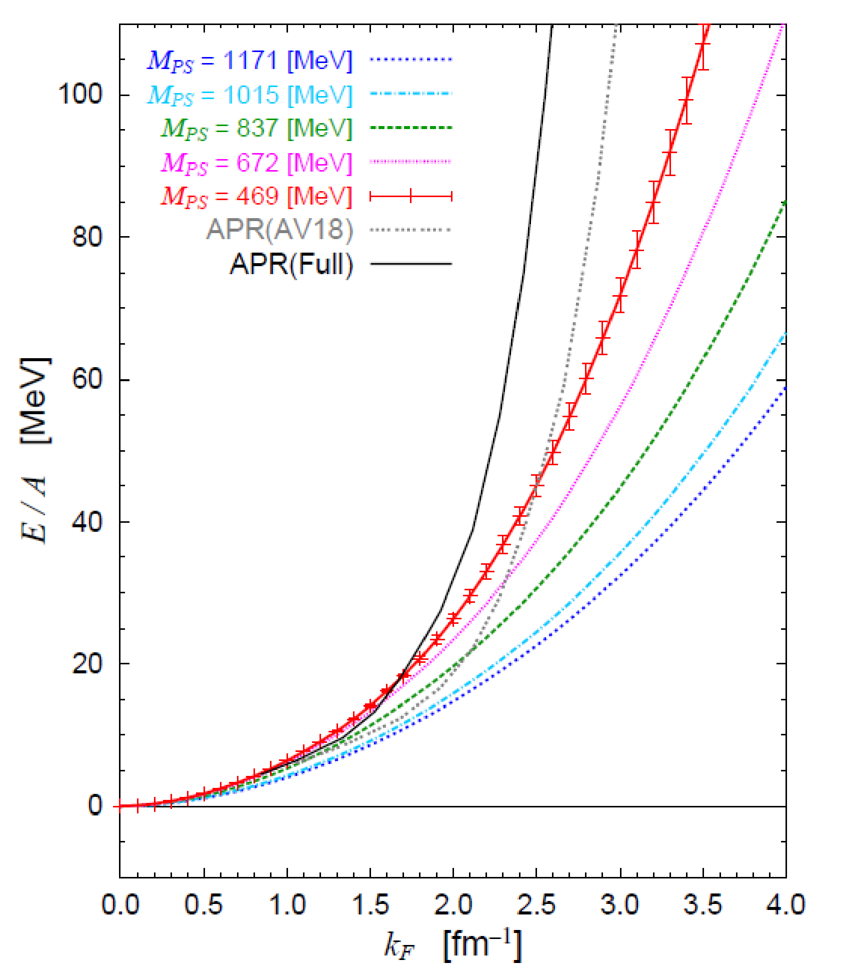
(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

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

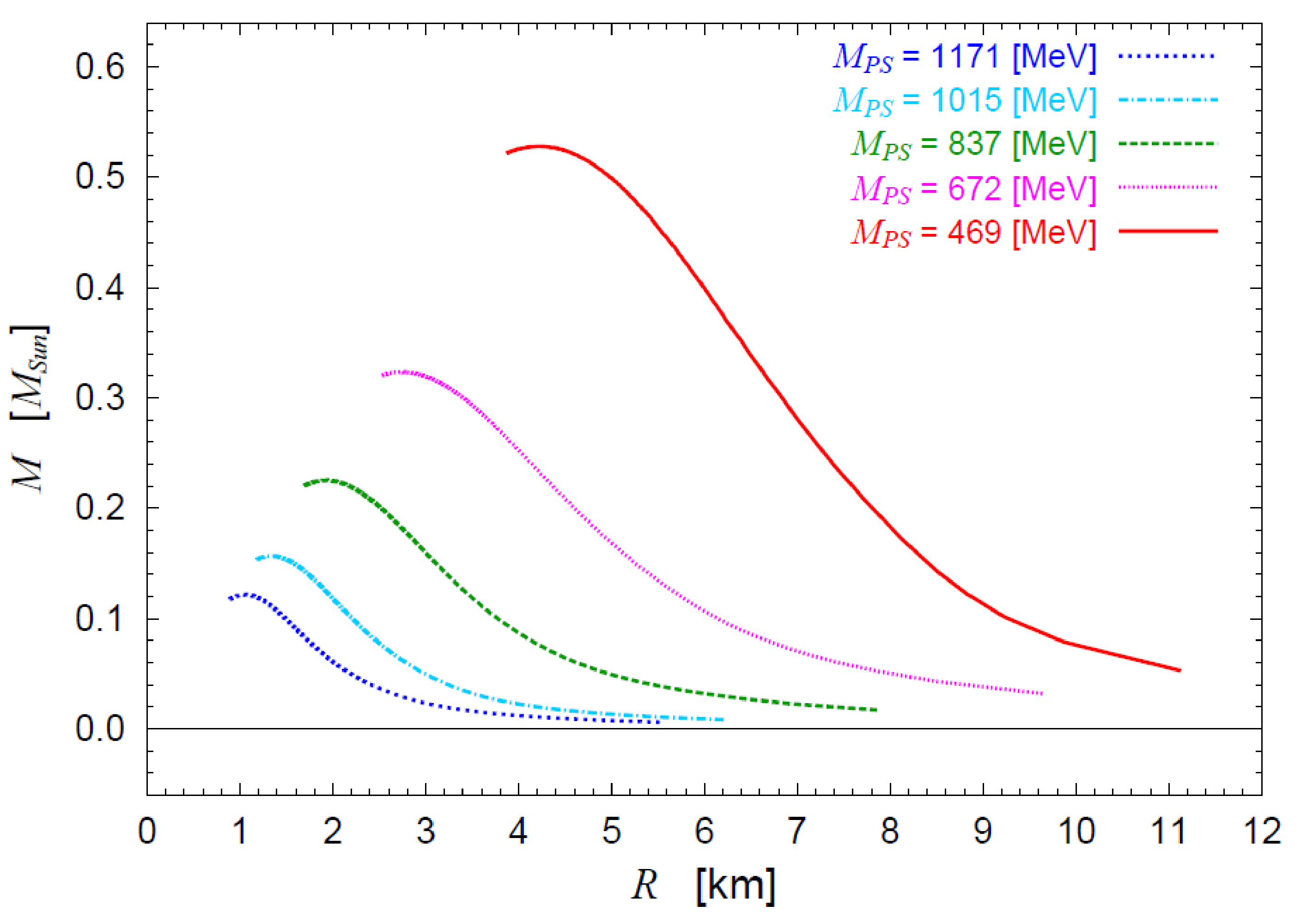
Nuclear Matter



Neutron Matter

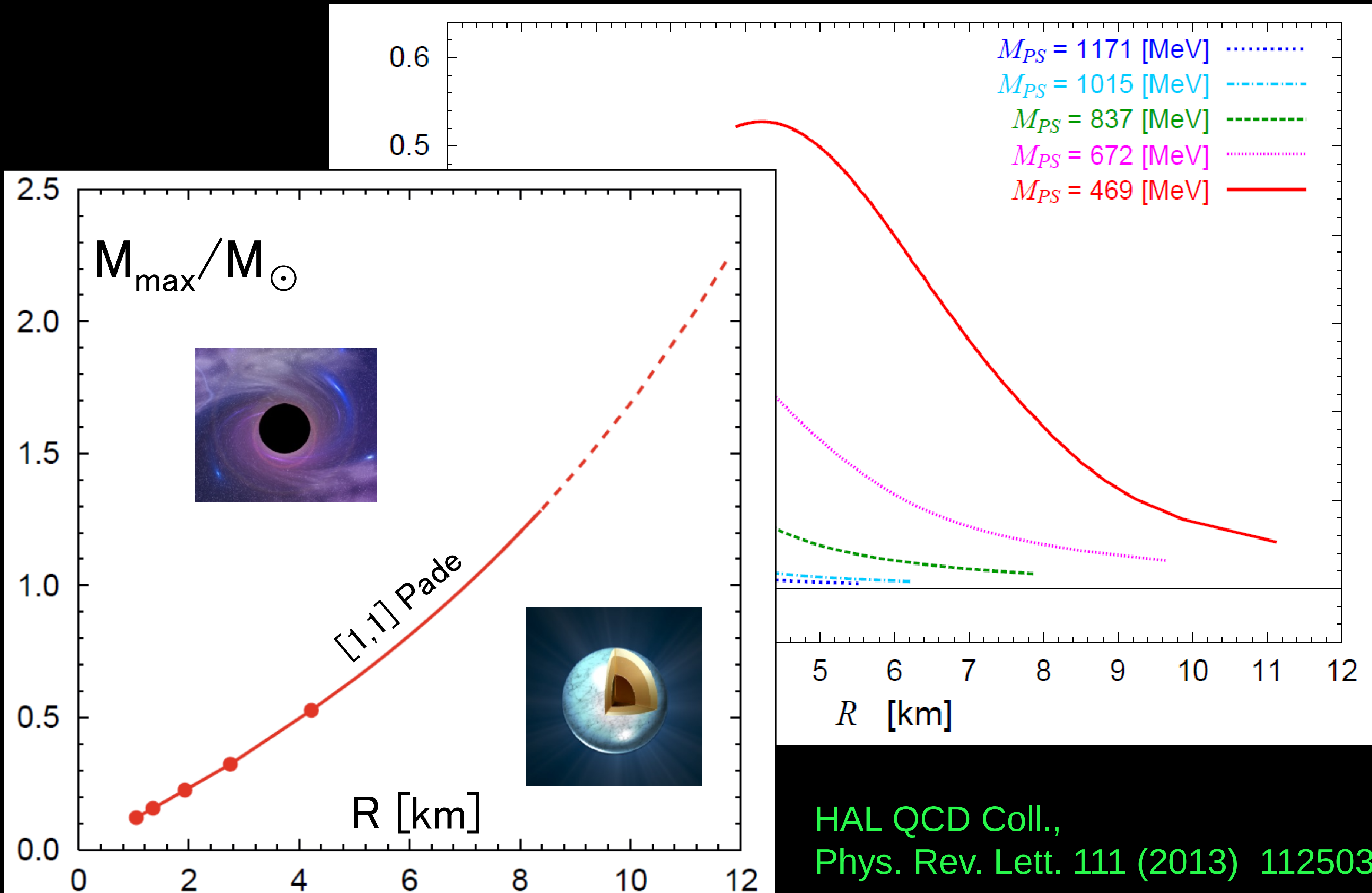


Neutron Star from “Lattice EOS”



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

Neutron Star from “Lattice EOS”



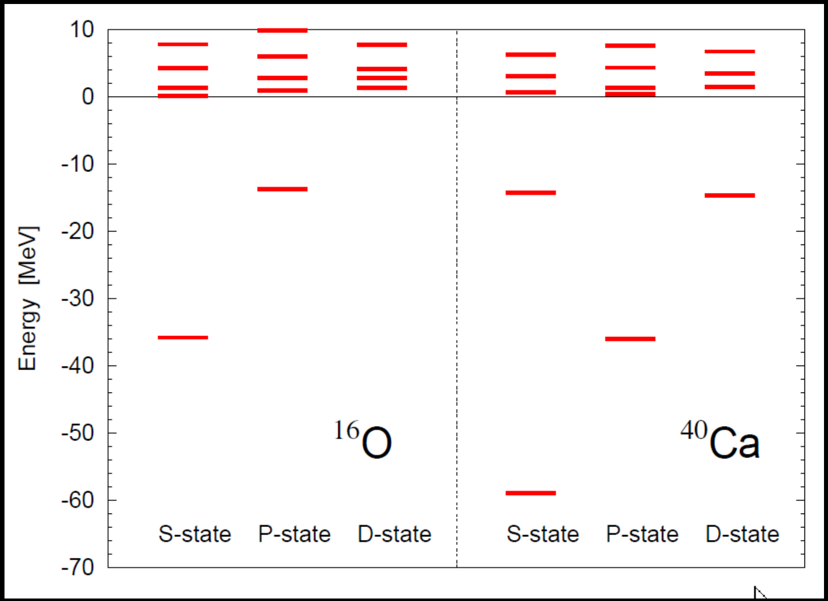
HAL QCD Coll.,
Phys. Rev. Lett. 111 (2013) 112503

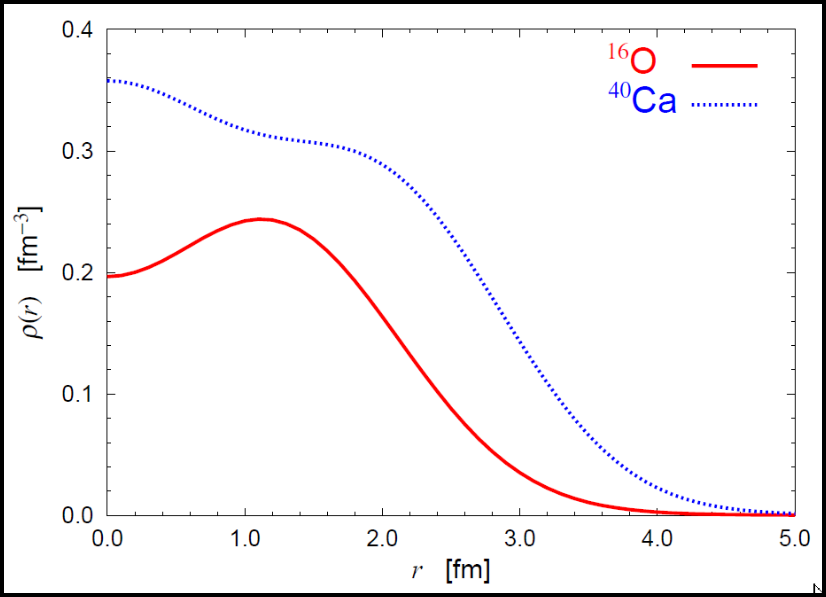
Finite Nuclei from Lattice NN force + BHF calculation

(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



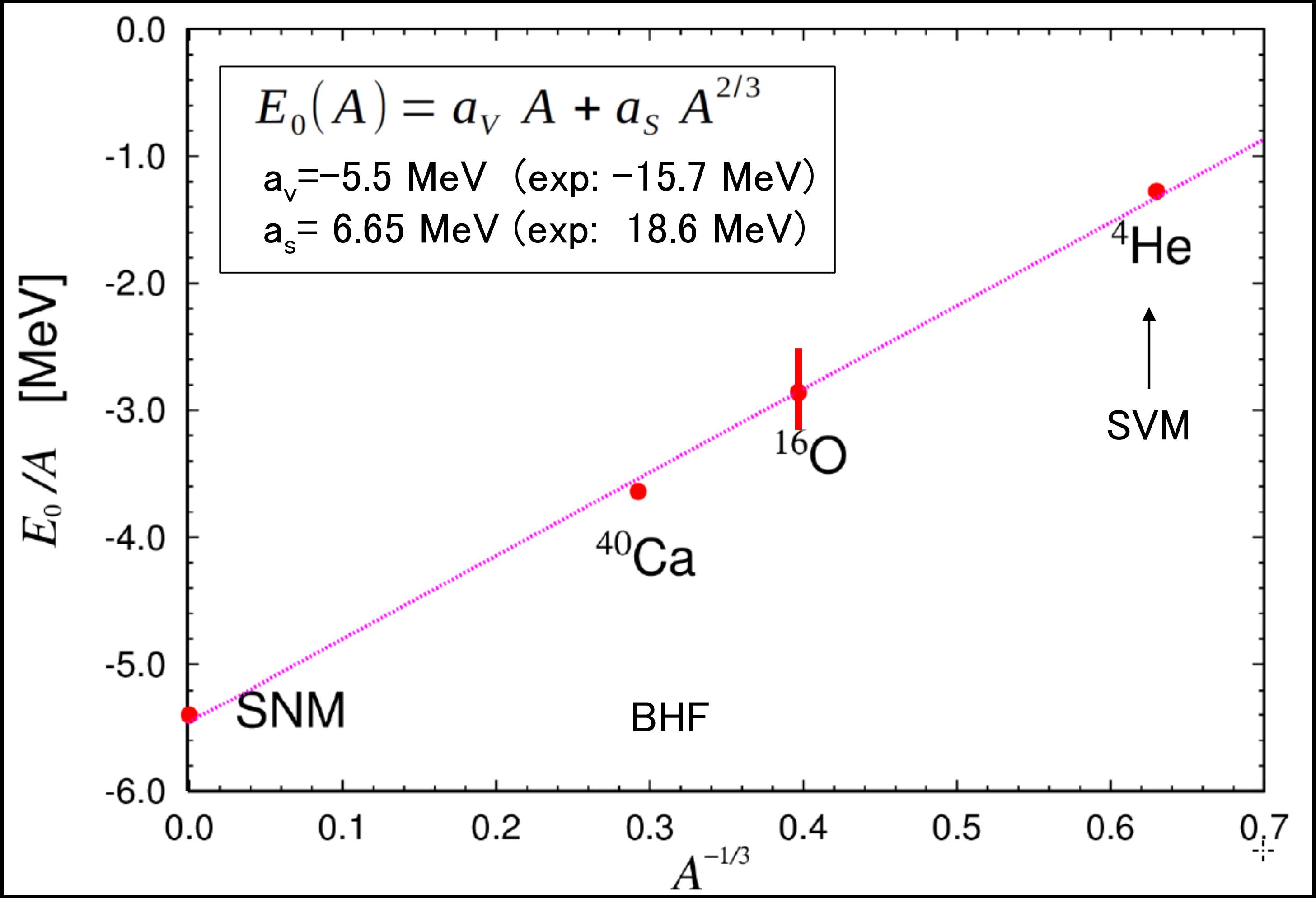


	Single particle level				Total energy		Radius
	$1S$	$1P$	$2S$	$1D$	E_0	E_0/A	$\sqrt{\langle r^2 \rangle}$
^{16}O	−35.8	−13.8			−34.7	−2.17	2.35
^{40}Ca	−59.0	−36.0	−14.7	−14.3	−112.7	−2.82	2.78

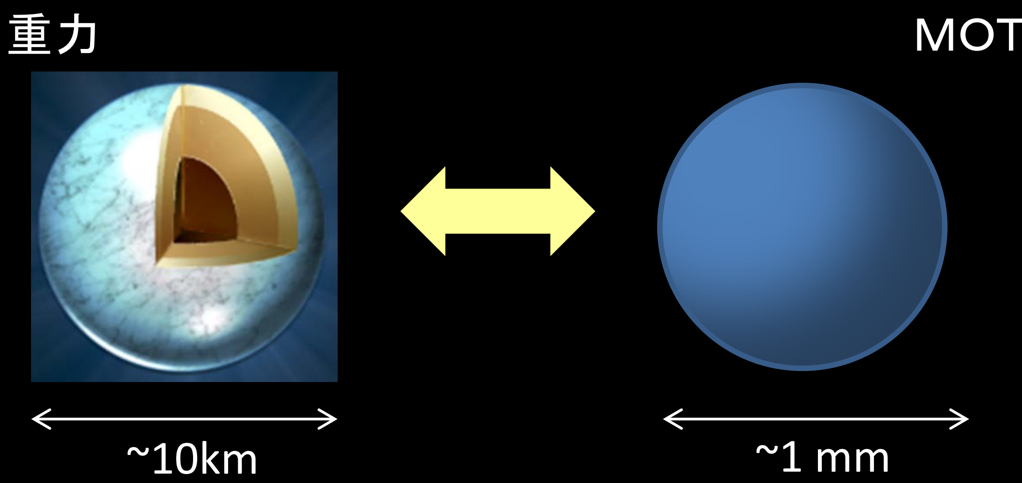
Nuclear Binding Energy from Lattice NN Force

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

Bethe−Weizacker behavior at m_π=470 MeV



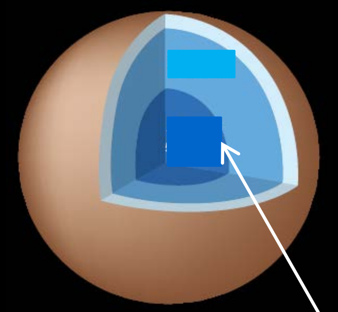
冷却原子を用いた
中性子星の実験室シミュレーション？



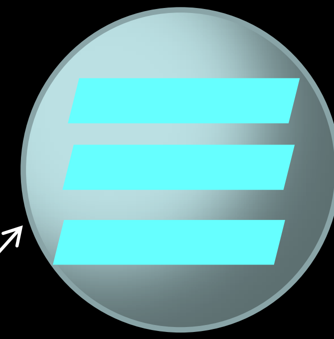
- ハドロン相とクォーク相のクロスオーバー
  ⇔ 冷却 ボース原子-冷却フェルミ原子混合気体
  Maeda, Baym & Hatsuda, Phys. Rev. Lett. 103 (2009) 085301
- π中間子凝縮 ⇔ 冷却双極子原子（分子）気体
  Meada, Baym & Hatsuda, Phys. Rev. A 87 (2013) 021604(R)

meson-condensation in ultracold dipolar atoms

Maeda, Baym, Hatsuda (2012)

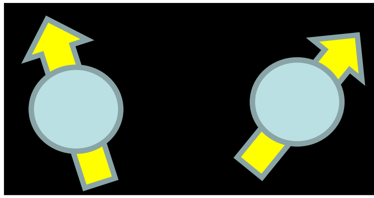


Neutron star ⟷ Trapped cold atoms



Meson condensate (SDW) by tensor force

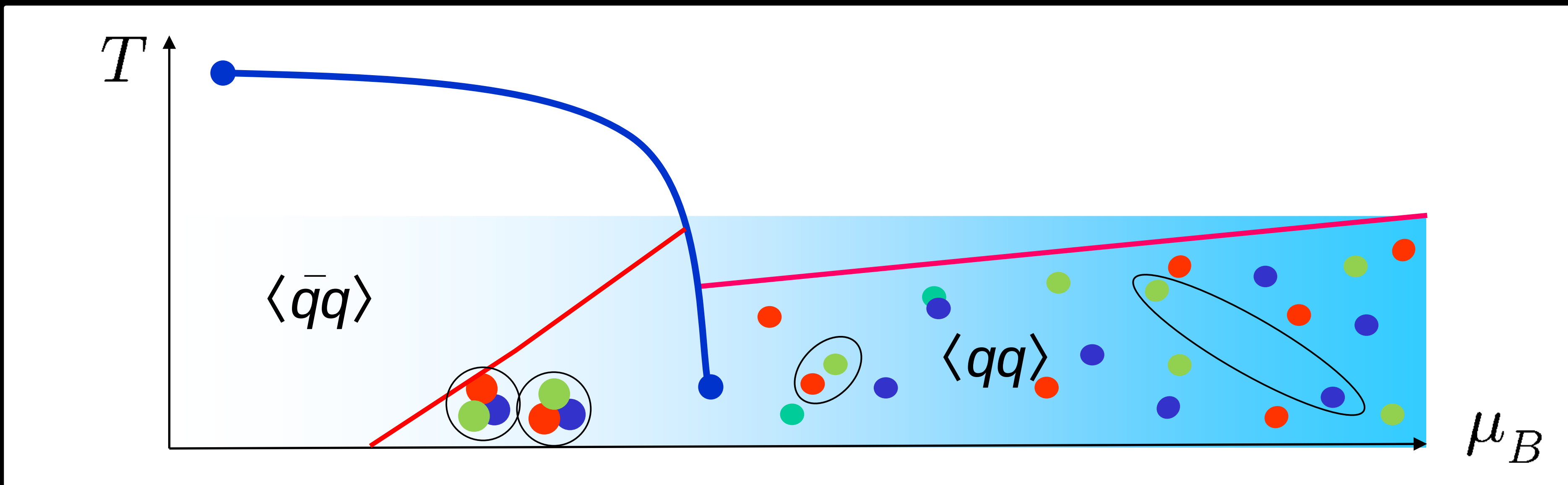
Dipole density wave (DDW) by dipole force



$$U_{dd} = -\frac{3(\vec{\mu}_1 \cdot \hat{r})(\vec{\mu}_2 \cdot \hat{r}) - \vec{\mu}_1 \cdot \vec{\mu}_2}{r^3} - \frac{8\pi}{3}\vec{\mu}_1 \cdot \vec{\mu}_2 \delta(\vec{r})$$

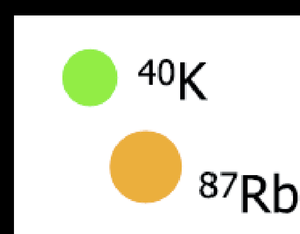
neutron matter	atomic dipolars
neutron stars	atomic gases(e.g. ^{163}Dy, ^{161}Dy)
neutrons	fermionic diplolars
spin	pseudo-spin (hyperfine states)
neutral vector meson (ρ^0)	photon
tensor-force potential	dipole-dipole interaction potential
meson condensation	spin/density wave

Hadron-Quark Phase Transition and the role of "Diquarks"



Nuclear superfluid ⇔ Fermion+Diquark ⇔ Diquark superfluid

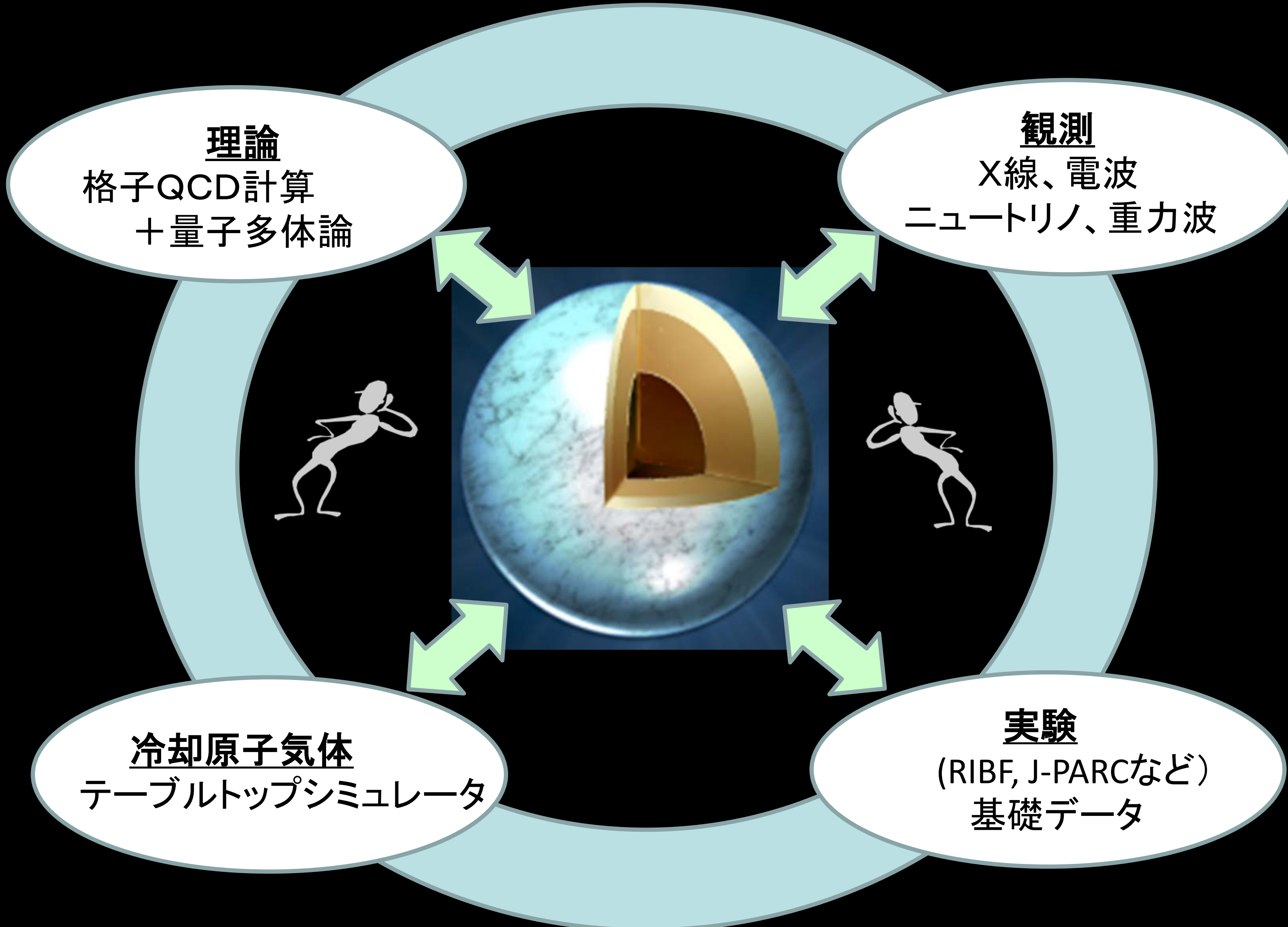
Induced superfluid ⇔ Fermi-Bose mixture



$$a_{\rm NN}^{\rm Born} = -\frac{m_{\rm N}}{2m_{\rm R}} a_{\rm bf}$$

Maeda, Baym & Hatsuda, Phys. Rev. Lett. 103 ('09)

まとめ



理論
格子QCD計算
＋量子多体論
観測
X線、電波
ニュートリノ、重力波
冷却原子気体
テーブルトップシミュレータ
実験
(RIBF, J-PARCなど）
基礎データ

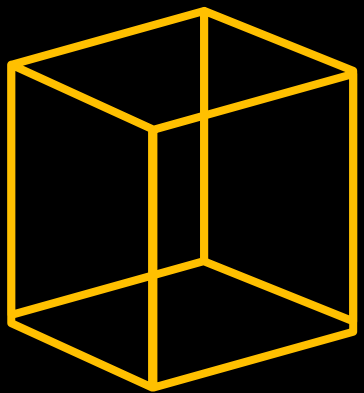
Present un-physical point simulation for single and multi-baryons

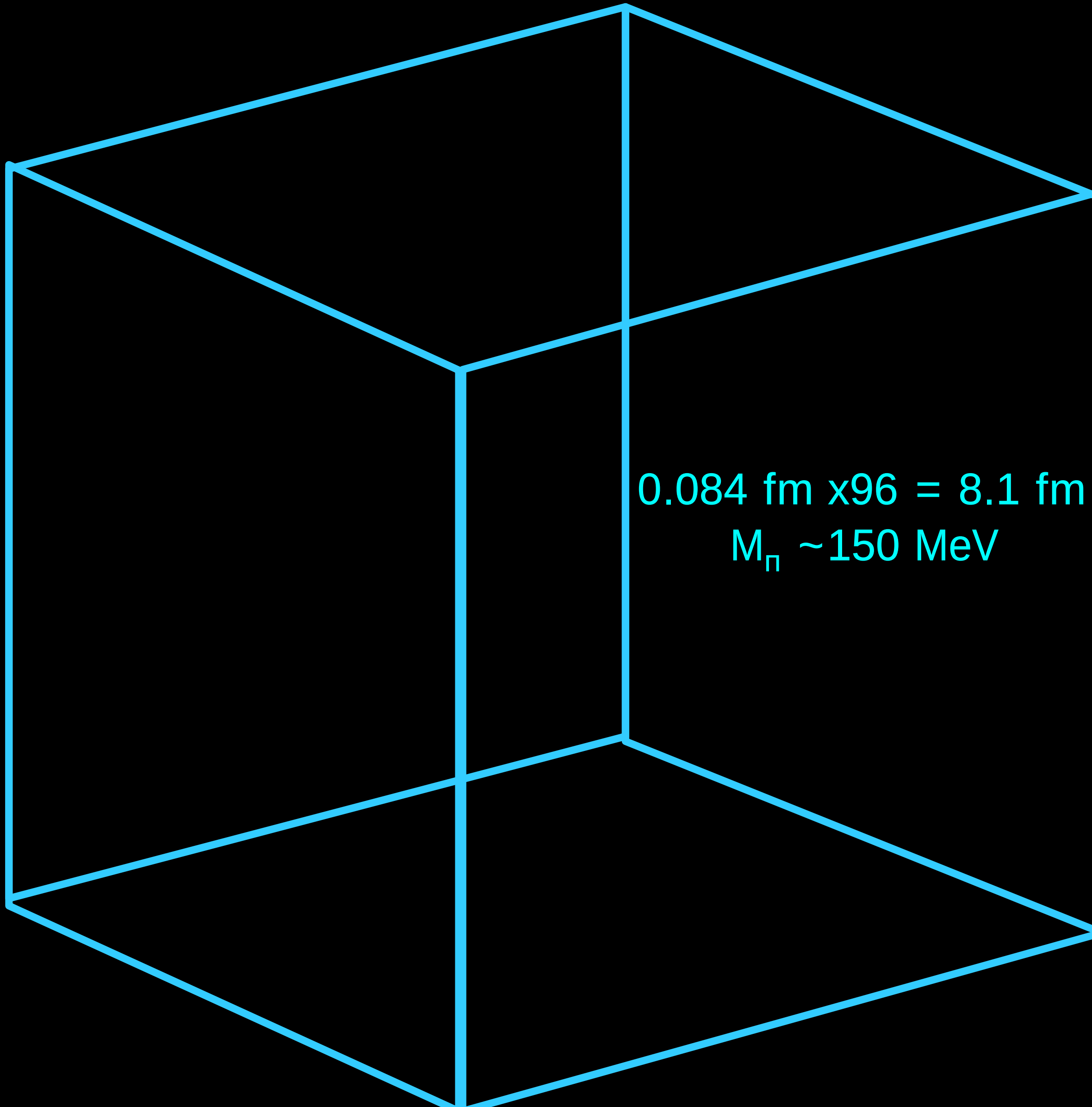
On-going physical point simulation for single and multi-baryons in K

NEXT YEAR'S TALK
Stay Tuned !!

TODAY'S TALK

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





END